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ORIGIN OF THE LARGE SPRINGS AND THEIR ALCOVES ALONG THE SNAKE RIVER IN SOUTHERN IDAHO[1]

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ABSTRACT

A group of large springs, eleven of which rank among the largest springs in the United States, discharge 5,000 cubic feet a second from the north side of the Snake River between Bliss and Twin Falls, Idaho. Most of the water issues from pillow lava at the base of basalt flows that fill ancestral canyons of the Snake River carved in the older lake beds of the region. Six different canyon fills of basalt, indicating six displacements of the Snake River in Pleistocene time, have been mapped in this area by the author.[2] Each of the flows that spilled into the Snake River Canyon caused a temporary lake on the upstream side of the lava dam and an alluvial fan containing huge blocks torn from the dam on the downstream side. Subsequent partial removal of the fans by the river has left concentrates of huge boulders in the form of trains, helpful in locating such displacements of the Snake River. Springs issue from these canyon fills of permeable basalt wherever the river has cut into them below the water table. Some of the springs issue from box-headed canyons or alcoves, which have been made by the springs, probably by solution of the basalt. It is believed that these springs are older than the others.

LOCATION AND DISCHARGE

Issuing from the north side of the Snake River Canyon in the 50-mile stretch between Twin Falls and Bliss, Idaho, are many large springs which have an aggregate discharge of more than 5,000 cubic

[1] Published with the permission of the Director of the U.S. Geological Survey.

[2] H. T. Stearns, L. Crandall, and W. G. Steward, "Geology and Ground-Water Resources of the Snake River Plain in Southeastern Idaho," *U.S. Geol. Surv. Water-Supply Paper* (in press).

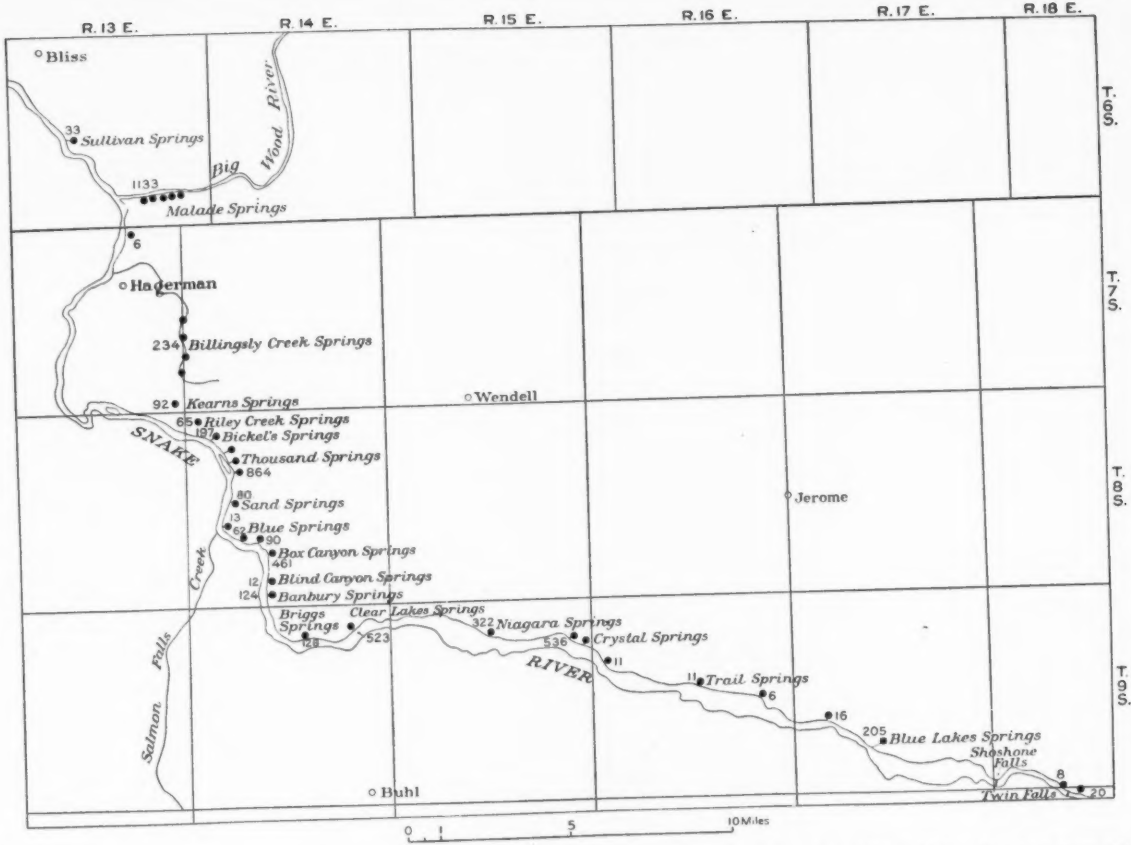

FIG. 1.—Map showing location and yield of the large springs on Snake River between Twin Falls and Bliss, Idaho. Numbers show yield of spring in second-feet. Most of the yields were measured in September or October, 1917, by Lynn Crandall, L. T. Burdick, and other engineers of the Twin Falls North Side Land and Water Co. Yield of Niagara and Sand Springs is that for September, 1918; of Thousand

feet a second and eleven of which rank among the largest springs in the United States (Fig. 1). Their aggregate flow would supply all the cities in the United States of more than 100,000 inhabitants with 120 gallons a day for each inhabitant.[3] Thousand Springs was the most spectacular of these springs before it was harnessed for water power (Figs. 2 and 3). Some issue from box-headed canyons or alcoves, only one of which receives surface drainage (Fig. 4). The water is

FIG. 2.—Thousand Springs before present power development. (Photograph by C. F. Bowen, *U.S. Geol. Surv. Water-Supply Paper 557*, Pl. 9.)

clear and has a temperature varying only a few degrees from 60° F. throughout the year.

PREVIOUS WORK AND PRESENT INVESTIGATION

Russell[4] was apparently the first to describe these springs in detail. He believed that they were supplied by water sinking in Big and Little Lost River sinks and from precipitation on the adjacent lava plain, and that the structure causing the springs was essentially that of horizontal lava sheets interstratified with sedimentary beds.[5]

[3] O. E. Meinzer, "Large Springs in the United States," *U.S. Geol. Surv. Water-Supply Paper 557* (1927), pp. 43–44, Fig. 12.

[4] I. C. Russell, "Geology and Water Resources of the Snake River Plains of Idaho," *U.S. Geol. Surv. Bull. 199* (1902), pp. 22–27, 162–66.

[5] *Ibid.*, p. 151 and Fig. 3.

Meinzer,[6] in his excellent description of these springs, summarizes the results of unpublished hydrographic surveys and the published account by Crandall.[7]

In 1928–30 the writer, with Lynn Crandall and W. G. Steward, made an investigation of the geology and underground-water resources of the Snake River Valley above King Hill for the United States Geological Survey, in financial co-operation with the Idaho

FIG. 3.—Near view of Thousand Springs, Idaho. (Photograph by C. F. Bowen, *U.S. Geol. Surv. Water-Supply Paper 557*, Pl. 9.)

Bureau of Mines and Geology, and the Idaho Department of Reclamation. The detailed report of this work awaits publication by the Geological Survey. The present article is a summary of one phase of the investigation and was presented as part of a symposium on ground water held by the Ground-Water Division of the United States Geological Survey in Washington in January, 1935. In the detailed report the writer has divided the rocks of the Snake River Basin of central southern Idaho into the units named in Table I.

[6] *Op. cit.*, pp. 42–51.

[7] Lynn Crandall, "The Springs of Snake River Canyon," *Idaho Irrig., Eng. and Agric. Societies Joint Conf. Proc.* (1918 and 1919), pp. 146–50.

GEOLOGY OF SPRING AREA

STRUCTURE AT SPRINGS

The numerous springs in almost all places issue from pillow lava or a peculiar glassy breccia at the base of a basalt layer, where it rests on older rocks. The pillows consist of spheroidal masses of lava of the same petrologic type as the basalt with which they are associated. They range from a few inches to 2 feet in diameter and con-

FIG. 4.—Blue Lake alcove, looking south into Snake River Canyon, Idaho. (Photograph by I. C. Russell, *U.S. Geol. Surv. Bull. 199*, Pl. 24.)

sist of a vesicular core changing outward to a dense glassy rind. Invariably they have numerous irregularly developed radial cooling cracks, especially near their surface, which make them break into small pieces. The pillows are loosely packed together in a matrix of comminuted friable basalt glass (Fig. 5). In many places much of this finer material has been carried out by spring water, and that which remains is commonly altered to a yellowish decomposition product resembling palagonite.

Downstream from the Thousand Springs the rock underlying the pillow lava in most places is the impermeable clay of the Hagerman lake beds (late Pliocene). At Thousand Springs the underlying rock is relatively impermeable stratified tuff in this same formation, but

TABLE I

GEOLOGIC FORMATIONS OF SNAKE RIVER BASIN, CENTRAL SOUTHERN IDAHO

Recent	Landslides and talus Alluvium, 0–20+ feet Loess, 10± feet
	Black lavas and cones, 100± feet
Pleistocene	Old alluvium, 100± feet Late Pleistocene basalt, 100± feet Wendell Grade basalt, 25± feet (black, aphanitic pahoehoe). *Type*, Wendell Grade, in road in Gooding Co., N.W. of town of Wendell.
	Minidoka basalt, 30± feet (vesicular, blue pahoehoe). *Type*, Minidoka dam; probably issued from one of cones near Minidoka. Burley lake beds, 150 feet in wells; not exposed. Deposited in ancient Lake Burley.
	Sand Springs basalt, 500± feet (massive pahoehoe flow). Exposed for 14 miles up Snake River, or to point where Sand Springs cascade into Snake River, in Gooding County. *Type*, wall of Snake River Canyon at Sand Springs cascade.
	Bliss basalt, 100± feet (chiefly vitreous porphyritic basalt; brecciated subaqueous flow). May be subaqueous phase of McKinney basalt or, possibly, of Sand Springs basalt. *Type*, Bliss Cone and Bliss Bridge, Sec. 11, T. 6 S., R. 12 E., Twin Falls County; also Bliss Spring, Gooding County.
	McKinney basalt, 20 feet on plains, 500 feet in Snake River Canyon (porphyritic, grayish-black pahoehoe). Issued from McKinney Butte, N.W. of Gooding. *Type*, McKinney Butte.
	Thousand Springs basalt, 100± feet (feldspar-olivine pahoehoe; filled with tubes and open contacts). Thousand Springs, S.W. of Wendell, in Gooding County, issue from this basalt. *Type*, bluff above Thousand Springs.
	Malad basalt, 400± feet (black pahoehoe). *Type*, cliff in Malad Canyon near Malad Power Plant.
	Madson basalt, 200+ feet (dense, black, jointed). Fills former canyon of Snake River carved in Hagerman lake beds. Madson Spring issues from this basalt. *Type*, cliff above Madson Spring.
	American Falls lake beds, 150± feet (buff, horizontal, evenly bedded, partly consolidated, clay, sand, and silt, including a 10±-foot member of gray pahoehoe basalt). *Type*, bluffs along Snake River from American Falls dam, Power County to narrows, 5± miles distant.
	Cedar Butte basalt, 200+ feet (aphanitic, blue, pahoehoe). *Type*, Cedar Butte, T. 8 S., R. 29 E. Power County.
	~~local~~~~~~~~~~
	Early undifferentiated basalt, 500+ feet.

TABLE I—*Continued*

Pliocene	Hagerman lake beds (upper Pliocene), 600± feet (nearly horizontal, partly consolidated, buff to white clay and silt, with, in most places, a gravel cap 20 feet thick; some pebbly lenses and sandy beds near top; in places some basic tuffs and flows; one thin basalt flow 200 feet below top is conspicuous for several miles along Snake River; contains a 20-foot bed of diatomite near mouth of Salmon Falls Creek). Late Pliocene fossils. Forms prominent bluffs along Snake River in Hagerman Valley, Gooding, and Twin Falls counties. *Type*, West bank Snake River at Hagerman.
	Banbury volcanics, 360± feet (massive, dark-brown weathered basalt flows and coarse and fine tuff beds). *Type*, exposures near Banbury Hot Springs, Sec. 33, T. 8 S., R. 14 E., Twin Falls County (*Upper Pliocene*).
	Raft lake beds (Middle[?] Pliocene), 200± feet (buff-colored clay, silt, and sand; in places filled with concretions; partly consolidated). In places unconformable on Paleozoic limestone. *Type*, exposures along Raft River, near mouth.
	Rockland Valley basalt (Middle[?] Pliocene), 250± feet (even-bedded blue and black, partly weathered; contains at least one bed of clay 15 feet thick in Rock Creek Canyon). *Type*, exposures on north side of Rockland Valley.
——(?)——	Massacre volcanics (Pliocene[?]; Lower [?] Pliocene), 150± feet (well-consolidated, red to brown, cindery basaltic tuff, in places containing angular fragments of underlying formations; at many places a persistent flow, 23± feet thick, of fine-grained blue basalt at base). *Type*, Massacre Rocks, Sec. 6, T. 9 S., R. 30 E. Power County, is the feeder from which these tuffs and lavas were erupted.
Pliocene (?)	Eagle Rock tuff (Pliocene[?]; Lower [?] Pliocene), 35± feet (rhyolite tuffs, in part welded obsidian). *Type*, Eagle Rock, northeast of Massacre Rocks, Power County.
	Neeley lake beds (Pliocene[?]; Lower[?] Pliocene), 100+ feet (flesh-colored to brown sandy lacustrine deposits, partly reworked tuffs). *Type*, in bluffs of Snake River in vicinity of village of Neeley, 5 miles southwest of American Falls.
——(?)——	Pillar Falls mud flow (Miocene[?]; Upper[?] Miocene), 0–40± feet (well-rounded gravel and huge boulders several feet in diameter; andesitic pebbles and boulders intermingled with ash and soil). *Type*, exposures at Pillar Falls.
Miocene (?)	Shoshone Falls andesite (Miocene[?]; Upper[?] Miocene), 200+ feet (purple and black, massive, vitreous, porphyritic). Forms Shoshone Falls and Pillar Falls. Rests on Paleozoic limestone. *Type*, Shoshone Falls.

upstream as far as Blue Lakes it is in most places the underlying slightly permeable Banbury volcanics. From Blue Lakes to Twin Falls it is massive andesite.

WATER-BEARING ROCKS

Although on casual examination the water-bearing basalt seemed to be a more or less continuous layer, detailed study showed that there were at least six and possibly seven different basalts that are conduits for the spring water between Twin Falls and King Hill. Most

FIG. 5.—Pillow lava at base of Sand Springs basalt, top of Clear Lakes grade. Note pillow in lower right foreground. (Photograph by H. T. Stearns, Neg. No. 729.)

of these basalts differ only slightly in petrologic characteristics, but all of them, with possibly one exception, differ sufficiently in field occurrence to make them readily susceptible of mapping. These basalts, named in order of their age from oldest to youngest, are (1) Madson basalt, (2) Malad basalt, (3) Thousand Springs basalt, (4) McKinney basalt, (5) Bliss basalt, and (6) Sand Springs basalt. The Sand Springs basalt may consist of two flows poured out at different times, and the Bliss basalt may be a subaqueous phase of the McKinney basalt. Mapping of each of these basalts showed that they fill or partly fill ancestral canyons of the Snake River adjacent to the pres-

ent canyon (Fig. 6). The best place to see one of these canyon fills of basalt is on the main highway opposite and upstream from the Thousand Springs power plant. The observer looking across the river at this point gets a magnificent view of a broad V-shaped section of the Sand Springs basalt, more than 300 feet thick, resting unconformably on older rocks. The bottom of the lava fill extends below the river surface, indicating that the old canyon was deeper than the present one. At this point the Sand Springs basalt is almost completely drained, but upstream numerous large springs issue from it. The manner in which lava-filled canyons serve as extensive collecting systems for underground water, discharging huge springs where tapped by erosion, has been described by the writer elsewhere.[8]

Madson basalt.—The Madson basalt, a dense, black, jointed basalt, crops out beneath the Malad and McKinney basalts in the east wall of the Snake River Canyon half a mile downstream from the mouth of the Malad River. It probably reached the Snake River by flowing down an ancestral canyon of the Malad. Steele and Madson Springs, and possibly Bliss Spring, are fed from this basalt, which has an exposed thickness of 200 feet.

Malad basalt.—Closely following the extrusion of the Madson basalt came a very voluminous flow of black pahoehoe lava that displaced the Snake River for at least 9 miles between the Malad River and Thousand Springs. This flow dies out as a thin wedge between the Madson and McKinney basalts near Steele Spring. It has been named the "Malad basalt" because it forms a 400-foot cliff in Malad Canyon. The Hagerman and Kearn tunnels, near Hagerman, expose 20–25 feet of pillow lava at its base. This basalt supplies all the water in Billingsly and Cove creeks and also the voluminous Malad Springs, which, because they yield more than 1,000 cubic feet a second, rank among the largest springs of the world.

Thousand Springs basalt.—The canyon carved in the older sediments by the Snake River after its displacement by the Malad basalt was filled with a very permeable porphyritic feldspar pahoehoe. Pillow lava or a related phase of comminuted glassy basalt characterizes the basal contact. This basalt, which is about 200 feet thick, is

[8] "Geology and Water Resources of the Upper McKenzie Valley, Oregon," *U.S. Geol. Surv. Water-Supply Paper 597* (1928), pp. 171–88.

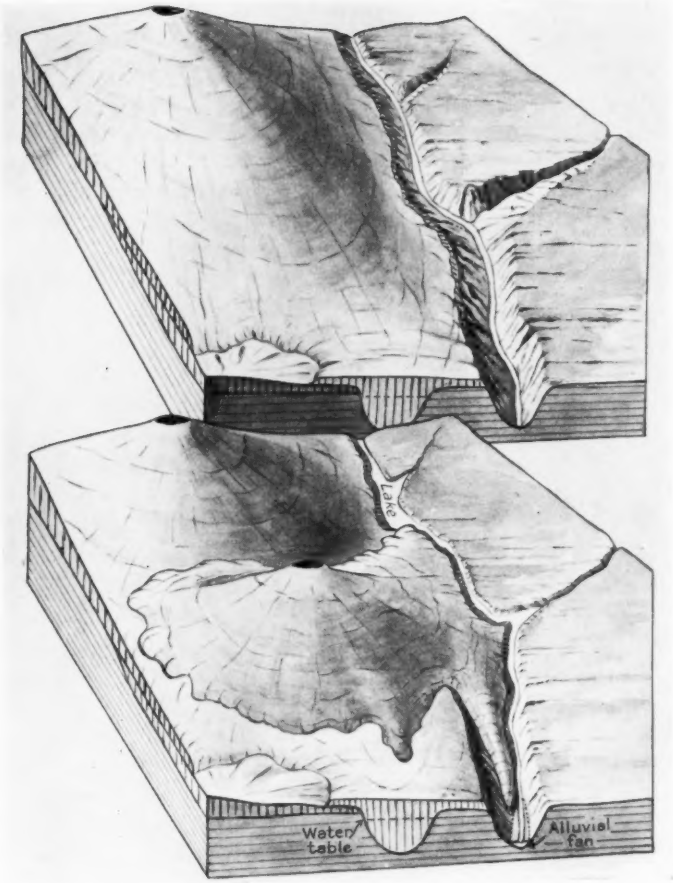

FIG. 6.—Diagram showing displacement of Snake River by lava flows

a great aquifer; all the large springs along the Snake River from Sand Springs to Riley Springs issue from it.

McKinney basalt.—McKinney Butte, at the foot of the mountains on the north, sent three streams of porphyritic lava into the Snake River Canyon. One of these lava flows made a fill in the canyon about 500 feet thick and displaced the river for a distance of 6 miles between Bliss and King Hill. Although extremely permeable, it carries very little water. Its supply is entirely dependent upon local rainfall because upstream leakage into it from the Snake River is prevented by a barrier of relatively impermeable basalt. Apparently lateral movement of water into it from the opposite side of the buried canyon is cut off by the same impermeable formation. The McKinney basalt, a prophyritic, grayish-black pahoehoe, named for McKinney Butte, supplies a small spring in Section 4, T. 6 S., R. 11 E. It has been described here because it crops out in the big-spring area and hence is part of the series of canyon fills. It is younger than the Malad basalt and is believed to be older than the Sand Springs basalt.

Bliss basalt.—A brecciated, vitreous, porphyritic basalt that was probably laid down under water crops out for about 7 miles downstream from the mouth of the Malad River. Several dikes and a large cone (Bliss Cone) are associated with it. It is very permeable, and from it issue several springs, notably Bliss Spring and the unnamed spring an eighth of a mile southeast. Its age is uncertain except that it is later than the Malad and Thousand Springs basalts. It is about 100 feet thick.

Sand Springs basalt.—Just upstream from Thousand Springs a V-shaped canyon fill of lava about 500 feet thick shows in the present Snake canyon wall. This, the "Sand Springs basalt," forms flat-topped, detached benches for 14 miles down the Snake River from the point where the Sand Springs cascade into the river, and completely fills an ancient canyon of the river for a long but unknown distance upstream. About 2½ miles downstream from Blue Lakes another V-shaped section of basalt is exposed in the wall of the Snake River Canyon. This may be another canyon fill of lava, but it could not be definitely established as different from the Sand Springs basalt, and may be only a large exposure of the side of the

Sand Springs canyon fill. If so, the Sand Springs basalt fills a former canyon of the Snake River for about 50 miles and supplies all the large springs from Twin Falls to Thousand Springs.

CAUSE OF PILLOW LAVA

From a few feet to 25 feet or more of pillow lava lies at the contact between these canyon-filling basalts and the older rock. It is most readily seen at the north end of the Twin Falls bridge across the Snake River, where the Sand Springs basalt rests on an older subaërial basalt. In Kearn tunnel 25 feet of pillow lava at the base of the Malad basalt rests on dry, mealy loess. In other places the pillow lava lies on tuffs, on older basalts, or on eroded lake beds. It seems to bear no relation to the character of the underlying formation. Moreover, pillow lavas were not observed at the base of the basalt sheets that do not fill canyons of the Snake River. Obviously this peculiar pillow phase is in some way connected with the conditions associated with the burial of the canyons.

Pillow lava of this type generally has been thought to be caused by lava flowing into water, but it is obvious from the conditions at most if not at all the outcrops in this area that the lava was spread over dry ground similar to the present surface. The following hypothesis is given to account for the presence of the pillow lava.

When a lava flow entered the Snake River Canyon it dammed the river and buried extensive saturated gravel deposits in the river bottom and also numerous pools of water. Much of this water trapped under the lava was converted into steam, which probably escaped chiefly at the contact of the lava with the canyon wall. It is highly probable that percolation from the ponded river continued through the gravel and brecciated base of the basalt throughout the period of eruption, and hence there was no lack of water. It is believed that the steam formed in this manner and escaping from the margins of the basalt gave rise to conditions essentially the same as those under which the usual subaqueous pillow lavas are produced and hence enabled pillow lavas to form at the base of these canyon-filling basalts far above the river bed.

GEOLOGIC HISTORY

Following the draining of the lake in which the Hagerman sediments were laid down voluminous basalt flows spread northward

from vents south of the present Snake River. These lava beds underlie the Twin Falls irrigation project and extend from Burley to the mouth of Salmon Falls Creek. During this volcanic epoch the Snake River probably flowed north of its present course, near the axis of the present Snake River Valley. After the cessation of the lava outpourings on the south side of the valley, sporadic eruptions on the north side began to crowd the river southwestward in this area (Fig. 6). The earliest known of these lavas is the Madson basalt, which was probably of insufficient volume to affect the position of the river materially. Erosion followed, during which the Snake River cut a canyon at least 400 feet deep. Then came the voluminous Malad basalt, entirely filling this canyon for at least 9 miles and displacing the river southwestward. The river then cut a new canyon farther southwest in the lake beds, but this canyon was only about 200 feet deep when erosion was halted by the outpouring of the Thousand Springs basalt. Another time of canyon-cutting at the southwest edge of this basalt came next, during which a canyon deeper than the present one was cut. This canyon later became filled in the stretch between Bliss and King Hill by the McKinney basalt, partly filled between Bliss and Malad Springs by the Bliss basalt, and upstream from Malad Springs probably as far as the town of Paul (near Rupert) by the Sand Springs basalt. After the Sand Springs eruption the river took a new course, partly along the south margin of the Sand Springs basalt, and carved the present canyon between Burley and Thousand Springs. Near Thousand Springs it tumbled back into its previous partly lava-filled canyon and began the task of removing these rocks.

EFFECTS OF DISPLACEMENT OF SNAKE RIVER BY LAVA FLOWS

The damming and displacement of the Snake River by these lava flows had four effects: (1) lake-bed sediments were deposited on the upstream side of the lava dams, giving rise to such deposits as the Burley and American Falls lake beds; (2) a new canyon was cut along the margin of the basalt where the lava was in sufficient volume to displace the river completely; (3) at the downstream end of the lava dam a fan was built containing huge blocks torn from the dam during its destruction. The formation of the fan at the toe of the dam resulted from the abrupt decrease in gradient at the point

where the river reached its old graded channel. (4) Finally, most of this fan deposit was removed, leaving a concentrate of the largest boulders as a train at the toe of the former dam, because, as the dam was cut away, the river changed from an aggrading to a degrading stream but lacked sufficient velocity to remove the big boulders. Such boulder trains are important criteria for recognizing volcanic accidents in the history of a river.

Irrigation projects are situated on both sides of the Snake River Canyon in the area of these springs. Because these lava-filled canyons on the north side of the river act as great underground drains, the irrigated lands on that side do not need artificial drainage, whereas those on the south side do. In a few places on the south side the water table has risen as much as 800 feet because of the lack of adequate drainage in the underlying rocks.

SPRINGS

TYPES OF SPRINGS

Two distinct types of springs were observed—those which discharge from the ends of canyon fills of lava where they have been cut through by the river and those which discharge from window-like exposures on the sides of the canyon fills. For example, a spring issues from the Thousand Springs basalt at each low spot or sag in the impermeable divide that separates this saturated basalt from the Snake River. Thus, these springs may be considered as discharging from spillways at successively lower levels downstream. Commonly these spillways are sufficiently numerous to drain the basalt fill almost completely, so that where it is finally cut entirely across by the river it yields little water.

SOURCE OF SPRING WATER

The water-table map prepared during the investigation indicates that the springs are supplied chiefly from water lost in the upper stretches of the Snake River Valley and from irrigation on the north side of the river. Additional water is derived from the surface drainage sinking in the lava beds on the north side of the valley and from precipitation on the lava plains.

The discharge of the springs increased from 3,885 second-feet in 1902, before any irrigation developments had been made on the north side, to 5,085 second-feet in 1918, after the north-side irrigation project had been developed.[9] The hydrograph of Blue Lakes Spring indicates that ground water flows through the basalt in the 15-mile stretch between the Wilson Lake region and this spring at an average rate of 750 feet a day.

TABLE II

APPROXIMATE AVERAGE ANNUAL CONTRIBUTIONS TO THE SPRINGS IN SNAKE RIVER VALLEY ABOVE KING HILL

(Based on studies of run-off prior to 1930)

	Acre-Feet
Big and Little Wood River areas	354,000
Big Lost River	226,000
Other creeks between Big Lost River and Henrys Fork	200,000
Henrys Fork	698,000
Snake River between Heise and Shelley	922,000
Losses from Lake Walcott Reservoir	100,000
Minidoka project	240,000
Twin Falls North Side project	600,000
Rainfall on lava plains	700,000
Total	4,040,000

POSSIBLE DEVELOPMENTS

The fact that the water supplying these springs flows through definite canyon fills of lava makes it possible to recover this water at certain points for the development of power. For example, by drilling a line of holes north of the river at Shoshone Falls it may be possible to locate one or more of these lava-filled canyons and partly drain them by a tunnel. Other similar developments might be made at power sites farther downstream. However, it should not be expected that such tunnels will recover all the water now discharging from these lava-filled canyons, because they probably receive contributions at numerous places from parallel lava-filled canyons to the north.

[9] Meinzer, *op. cit.*, p. 43.

SPRING ALCOVES

ORIGIN

Many of the big springs discharge from box-headed canyons or alcoves that receive no surface drainage and hence must have been made by the springs themselves. The most notable are Blue Lakes, Box (Fig. 7), Blind, and Malad canyons. Some are dry, like the unnamed ones near Shoshone Falls and those in the Lake Channel re-

FIG. 7.—Head of Box Canyon showing absence of talus in spring pool. (Photograph by H. T. Stearns, Neg. No. 727.)

gion southwest of American Falls, and are partly filled with talus, alluvium, or wind-blown sand. Russell, who first recognized these alcoves as due to spring action, describes them as follows:

> At Blue Lakes, about 5 miles below Shoshone Falls, where the walls of Snake River Canyon are about 700 feet high and nearly vertical, except for the talus lodged against their bases, there is a tributary canyonlike alcove in the north wall which is about 2 miles long and about 2,000 feet across at the top and which heads in a semicircular amphitheater with vertical walls about 300 feet high. There is no stream entering the alcove from the surface of the neighboring plain, but springs discharging probably several hundred cubic feet of water per second boil up in the amphitheater at its head. One of the striking features in this alcove is the small quantity of talus at the bases of the bordering cliffs. This is

most noticeable in the semi-circular expansion of the alcove at its head. In the view of the Blue Lake alcove presented on plate 24 [Fig. 4 of this article] some of the features referred to may be recognized. . . . .

These pools and others fed by springs in and near the four alcoves referred to have white bottoms composed of clean white sand which is brought to the surface of the springs themselves. . . . . No exposures of the material on which the basalt rests are known to me, but as the springs are bringing out white silt and fine white quartz sand it is evident that beds of similar material exist beneath the basalt.

The origin of the side canyons which receive no surface streams, such as Little and Box Canyons and the one in which the Blue Lakes are situated, is plainly due to the action of the great springs which come out at their heads. The lower portion of the canyon of the Malad has a like history, modified by the fact that a surface stream is also concerned in the work. The great springs undermine the basalt by removing the soft material on which it rests. Thus blocks of the usually more or less vertically jointed rock break away and fall into the spring and sooner or later sink into the soft bed beneath, as the emerging waters remove the silt and sand from beneath them. By this process vertical walls without talus slopes are produced. This process continuing, the cliff recedes, leaving a side cut or alcove in the wall of the main canyon, which becomes lengthened into a lateral canyon. The process would seem to be cumulative, as the farther the head of a side canyon receded the greater would be the tendency of the escaping waters to converge toward it. The marked tendency to an enlargement into an amphitheater, observable especially at the head of the Blue Lakes alcove, is apparently due to this cause.[10]

Three hypotheses for the origin of the alcoves are considered—sand burial, erosion, and solution.

The sand-burial hypothesis calls for a layer of sand at the bottom of each alcove sufficiently thick to engulf the basalt removed in the development of the alcove. Careful search proved that the white sand in Blue Lakes was typical blow sand from the adjacent river flood plain, also that the basement beneath the Blue Lakes alcove consists of the relatively impermeable Banbury basalt, and not strata of quartz sand. Furthermore, Shoshone Falls andesite forms the basement of the Devils Corral alcove, in Section 32, T. 9 S., R. 18 E., and of several others in the stretch of the Snake River Canyon between Twin Falls and Blue Lakes. Some of these alcoves are dry and now lie high above the level of the Snake River, hence their basement can be examined. The talus postulated by Russell[11] in the floors of these alcoves is absent, and a sharp contact between the ba-

[10] *Op. cit.*, pp. 127, 128. [11] *Ibid.*, p. 130.

salt and andesite is visible. The postulated presence of soft sand or silt strata of sufficient thickness to engulf a block of basalt 400 feet thick and equivalent in size to the alcove, without any exposure in the adjacent Snake River Canyon, is one of the weak features of this hypothesis. Tunnels driven to tap the spring water in several places along the Snake River Canyon have found the spring water moving through interstices in basalt where it rests on impermeable rock formations.

The conspicuous feature about these alcoves is the scantiness of talus at their heads and its abundance along the alcove walls downstream, as shown in Figure 7. Inasmuch as the spring at its point of issue is clear and has a low velocity, the second hypothesis or that of erosion does not seem adequate to explain these alcoves. In many of the alcoves the water flows swiftly between the spring pool and the Snake River and is armed with quartz sand blown from the river valley, yet the talus is not being removed as rapidly as at the head of the alcove.

The third hypothesis requires the slow solution or chemical weathering of the basalt in the clear water of the spring pool. Chemical weathering results in the breaking-down of the minerals of the basalt into carbonates, chlorides, and sulphates and in the solution of these salts. The nature of these changes is discussed at length by Clarke.[12] As Wentworth[13] expressed it: "Basalt is generally recognized as offering rather slight resistance to chemical weathering, because of the relative instability of such minerals as augite, olivine, and plagioclase feldspar as compared with quartz and orthoclase."

The mean temperature of the spring water is only 10° F. below the mean temperature in the Hawaiian Islands, where basalt boulders fluted by rainwater solution are common. Analyses of the water from several of these springs and adjacent wells were made. The samples were too few to give a conclusive answer to the problem, but were sufficient to indicate that the spring water is not appreciably

[12] F. W. Clarke, "The Data of Geochemistry," *U.S. Geol. Surv. Bull. 770* (5th ed., 1924), pp. 479–542.

[13] C. K. Wentworth, "Principles of Stream Erosion in Hawaii," *Jour. Geol.*, Vol. XXXVI (1928), p. 390.

higher in mineral content than the tributary ground water. However, the volume of water discharged by these springs is so great that if the water dissolved only 5 parts per million of solids after it issued, solution would be competent to form the alcoves in the estimated time since they originated.

ALCOVE PIRACY

The presence of numerous dry alcoves suggests the question: Why and how did they dry up? It is at once evident that an explanation which will fit one group of dry alcoves may not fit others, because of the differences in the kinds of rock involved and in the form of the land surface flooded by the basalt. Another question is: Why do some springs have alcoves and others not?

The following hypothesis is offered to account for the variation in size and shape of the alcoves and the variation in the amount of water rising in those supplied by the Sand Springs basalt.

When the Sand Springs basalt was erupted the Snake River was displaced from half a mile to 5 miles south of its old canyon and forced to find a new channel. Then the river began to erode a canyon to the baselevel of the river bed at the downstream end of the Sand Springs basalt, near the mouth of the Malad River. The water table in the Sand Springs basalt adjusted itself to the point of discharge, which at first was where the river tumbled back into its former partly lava-filled canyon. This place was shown by geologic mapping to be at the mouth of Salmon Falls Creek, near Thousand Springs. Here the first springs should have developed, because upstream from this point the river was presumably flowing above the water table on the surface of the lava plain. It therefore is not surprising to find at this point the best-developed alcoves—namely, Box and Blind canyons, each over a mile long. Between this place and Blue Lakes numerous large springs, such as Clear Lake, issue, but they have not formed alcoves or have made only slight indentations in the valley wall. It is believed that the absence of alcoves at these springs indicates that they are relatively young. This explanation is supported by the fact that the divide between the Snake River and the Sand Springs basalt-filled valley in this stretch is the relatively impermeable Banbury volcanics. At Blue Lakes the divide is formed by permeable

basalts, and hence ground water had an opportunity to enter the river at this point early in the history of the present canyon. Accordingly, at this point a large alcove exists similar to Box and Blind canyons.

A series of diagrammatic cross sections are given in Figure 8 to explain these differences in history. Section 1 of Clear Lake represents the geologic conditions in the vicinity of Clear Lake, Niagara, or Crystal Springs prior to the extrusion of the Sand Springs basalt and shows the Snake River Canyon incised in the relatively impermeable Banbury volcanics at the margin of younger basalt. Section 1 of Blue Lakes shows geologic conditions at the same stage in the vicinity of Blue Lakes. The important difference between the two sections is the thick series of permeable basalt beds overlying the relatively impermeable Banbury volcanics at Blue Lakes.

Section 2 at Clear Lake shows the geologic conditions after the canyon was filled with the Sand Springs basalt and before the Snake River had established a new course. The water table is close to the surface in the lava fill, because the baselevel of ground-water flow was established by the outlet of this water at Box Canyon Spring, near Hagerman Valley. The water-table conditions at Blue Lakes at this time were very similar.

Section 3 at Clear Lake shows the conditions after the river had cut a canyon about 100 feet deep at the southern margin of the Sand Springs basalt. The banks of the river consist of the relatively impermeable Banbury volcanics, hence the ground water moving through the lava-filled channel is not affected by the new canyon and continues to flow westward toward Box Canyon, its nearest outlet. At the same stage in the vicinity of Blue Lakes ground water in the lava-filled valley had already begun to escape into the river through the permeable basalt divide.

Section 4 shows a still later stage of river-cutting. In the vicinity of Clear Lake the water table was still in the same position, undisturbed by the presence of a fairly deep canyon adjacent to it because of the impermeable divide between them. At the same stage at Blue Lakes an alcove had already formed because water readily entered through the permeable divide between the old and new canyons. Considerable water was still moving westward through the lava fill,

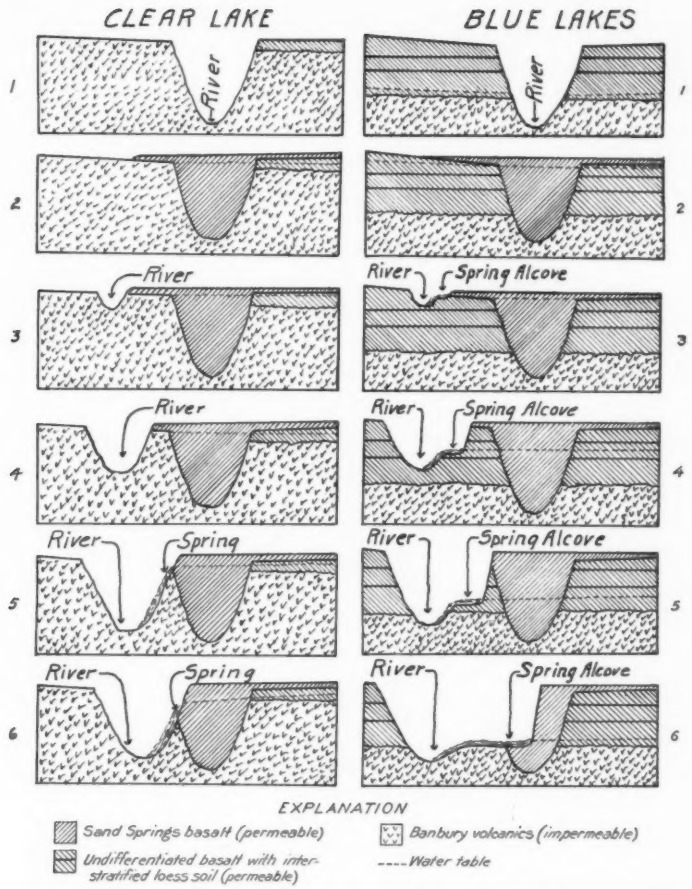

FIG. 8.—Diagram showing formation of Clear Lake and Blue Lakes springs, looking downstream.

because the Blue Lakes outlet was still considerably higher than the bottom of the ancient canyon. West of Blue Lakes additional ground water probably entered the lava fill from the north, and this recharge accounted for the high level of the water table as shown in the section.

Section 5 shows the Snake River Canyon at Clear Lake in a more advanced stage than in section 4. In the process of deepening, the canyon had been widened sufficiently to reduce the impermeable divide slightly between the old and new canyons. Water in the lava fill found an outlet and began to overflow at low points in this divide in the stretch between Blue Lakes and Box Canyon, leading to the formation of Clear Lake and the adjacent springs. The level of the water table was consequently lowered by this overflow of ground water into the river. In the meantime, the Blue Lakes alcove was deepened slightly and migrated northward, as shown in section 5. The old basalt divide has practically disappeared, but the deepening of the alcove was arrested by the spring cutting down to the Banbury volcanics.

Section 6 shows the present stage of the Snake River Canyon at Clear Lake. The long erosional epoch has widened the canyon, thereby reducing the height of the impermeable inverted wedge-shaped divide between the old and new canyons. The springs have increased considerably in discharge, and the water table has been lowered. Probably the increase in the flow of these springs accounts in part for the drying-up of Blind Canyon, which was less favored by the underlying structural conditions than the adjacent Box Canyon. At Blue Lakes the alcove has receded northward until a considerable part of the lava fill in the old canyon has been removed, as shown in section 6. In spite of its steep gradient, the Clear Lake water, being unarmed with abrasive sand, was not able to cut through the Banbury volcanics and keep the spring channel at the same level as the Snake River. For this reason considerable water is still moving westward through the unexposed parts of the lava fill and helping to supply the springs farther west. The deepening of the Blue Lakes alcove dried up the numerous alcoves upstream from it, because at these alcoves the impermeable Shoshone Falls andesite occurred at much higher levels than that of the Banbury volcanics at the Blue Lakes.

GEOLOGY OF A PORTION OF THE SAVANT LAKE AREA, ONTARIO

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ABSTRACT

Approximately 18,000 feet of sediments, divisible into six members, and 27,000 feet of volcanics below and above these sediments make up the early pre-Cambrian geologic column in the Savant Lake area. These rocks have been folded, intensely faulted, and subjected to at least one period of granitic intrusion and two periods of basic dike intrusion. In the sediments, and especially in the lavas, primary structures were found to be of great value in working out the structure. Correlation was attempted only with the Sioux Lookout and Sturgeon Lake areas.

The genesis of the two iron-bearing members is considered. Microscopic evidence suggests the possibility of formation through selective replacement by hydrothermal solutions. Other evidence points to a syngenetic origin.

INTRODUCTION

In the summer of 1927 Dr. E. S. Moore and assistants mapped what is now known as the Savant Lake area for the Ontario Department of Mines.[1] Due to the size of the area (approximately 1,000 square miles) and limited time, the geological work was necessarily of a reconnaissance nature. This paper deals with a portion of that area, roughly bounded by latitudes 50°19′ and 50°30′ and longitude 90°42′ and 90°25′, including Poisson and Jutten townships and the two unsurveyed townships to the west. The object of the work was:

1. To establish the sequence of formations, their thickness, conditions of deposition, and relations to the basic lavas and to the intrusives.

2. To study the iron formation and, if possible, determine its genesis.

3. To work out the structural geology.

As the field work progressed and the intricate nature of the structural relationships became apparent, the writer realized that in the time available it would be impossible to map the entire area in as great detail as originally planned. At the same time he realized that

[1] E. S. Moore, "Lake Savant Area, District of Thunder Bay," *Ont. Dept. Mines*, Vol. XXXVII, Part IV (1928), pp. 53–82.

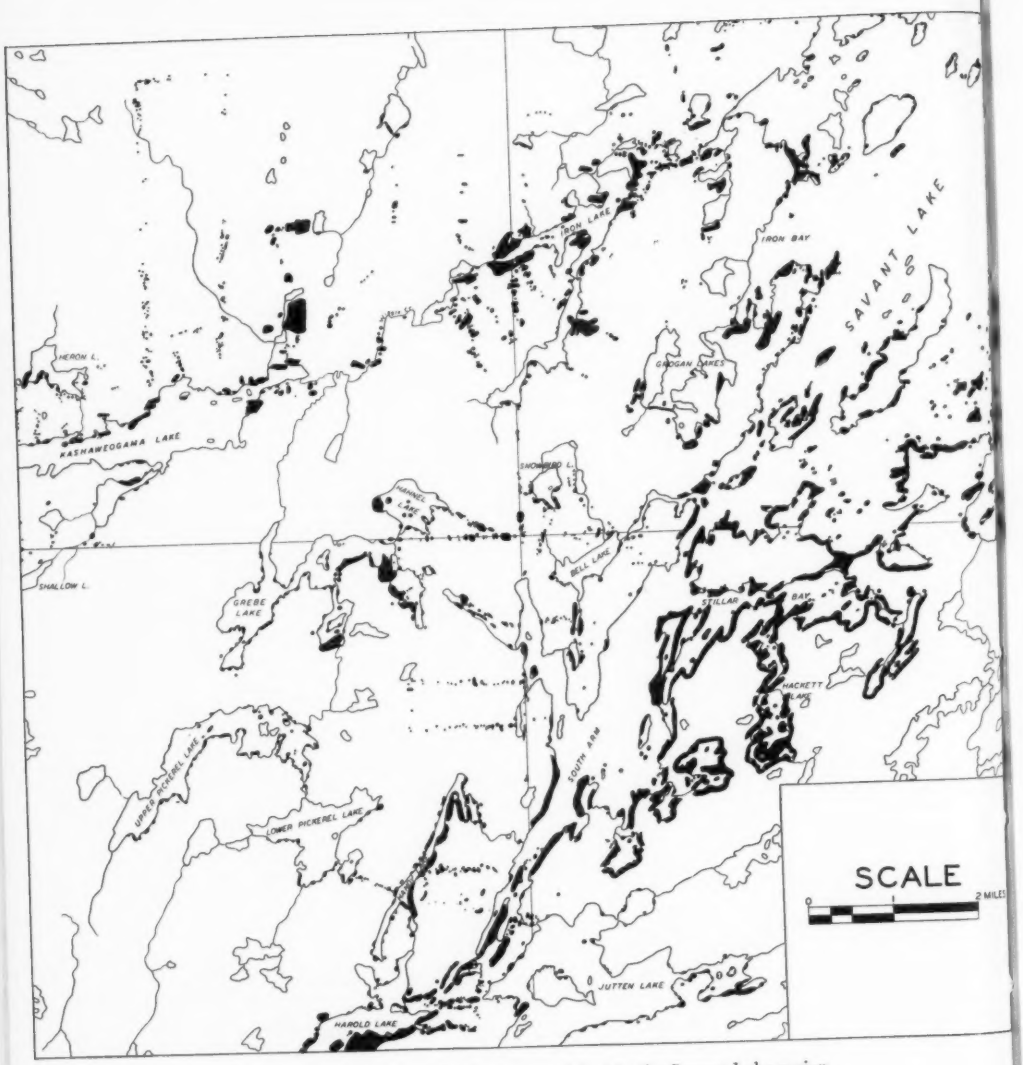


FIG. 1.—Areal distribution of outcrops visited in the Savant Lake region

the major structures were of large dimension and could not be satisfactorily worked out in an area smaller than that originally chosen. The geological work is, therefore, much less complete than desired.

PREVIOUS WORK

Earliest reference to the Savant Lake area was made by McInnes,[2] who in 1901 visited the main lake during the course of a geological reconnaissance of the country lying between Sturgeon Lake and Lac Seul. In the same year Sullivan[3] made a hasty examination of the glacial gravels on islands of the main lake, but no bedrock observations were recorded. In 1903 Miller[4] traversed Savant Lake and reported in some detail on the gold found in the glacial drift. Reference was also made to the magnetite deposits.[5] In 1906 Collins made a more complete reconnaissance of the district, recorded his observations in two papers,[6] and published the first geological map of the area. Collins described the bands of conglomerate and indicated the distribution of the iron-bearing formation, the sediments, and the greenstones, all of which were combined as Keewatin in the mapping.

In 1909 Moore, engaged in a geological survey of the magnetite deposits of the Savant Lake area, presented a relatively detailed report and a map of an area lying between Kimmewin and Savant lakes.[7] The various types of rocks were described, the structural geology considered, and the magnetite deposits discussed from the standpoint of composition and genesis. In 1926 lode deposits of gold were discovered, and during the following summer Moore undertook

[2] W. McInnes, "Region South-east of Lac Seul," *Can. Geol. Surv. Summary Rept.*, Vol. XIV, Part A (1910), pp. 94–95.

[3] W. T. Gibson, *Ont. Bur. Mines*, Vol. XI (1902), p. 18.

[4] W. G. Miller, "Mines of Northwestern Ontario," *Ont. Bur. Mines, Ann. Rept., 1903*, pp. 87–90.

[5] *Ibid.*, p. 313.

[6] W. H. Collins, "On Surveys along the National Transcontinental Railway Location between Lake Nipigon and Lac Seul," *Can. Geol. Surv. Summary Rept.* (1906), pp. 106–7; "A Geological Reconnaissance of the Region Traversed by the National Transcontinental Railway between Lake Nipigon and Clay Lake, Ontario," *Can. Geol. Surv. Bull. 1059* (1909), pp. 34–37.

[7] E. S. Moore, "Lake Savant Iron Range Area," *Ont. Bur. Mines 19th Ann. Rept.*, Vol. XIX, Part I (1910), pp. 173–92.

a resurvey of the entire Savant Lake area. This report[8] is by far the most comprehensive and accurate study of the Savant Lake area published. The general essentials of the geology were recognized by Moore.

General Geology

General Statement

The stratigraphic succession as now known in the Savant Lake area is shown in the accompanying geologic column (Table I). The oldest rocks, here named the "Jutten volcanics" from their excellent exposure in Jutten Township, indicate a period of intense volcanic activity during which was formed a great volume of intermediate and basic flow rocks with some interbedded tuffs, agglomerates, conglomerates, graywackes, and acid flows. This series was tilted or folded, intruded by granitic rocks, and then deeply eroded.

Upon this erosion surface, near a region of strong relief, was deposited a thick terrestrial conglomerate composed of detritus from the greenstone-granite terrain. After the deposition of a thousand feet of this conglomerate, conditions changed greatly, probably owing to the initiation of volcanism, and a very thick conglomerate deficient in granite detritus was deposited. These coarse clastics, forming the Lower Savant series, were followed by deposition of four finer-grained members, two containing interbedded iron formation[9] and two essentially graywacke,[10] which may be designated the "Upper Savant series." A period of erosion followed the deposition of these dominantly sedimentary rocks. Then volcanic activity was again renewed; and a very thick series of tuffs (the Handy Lake volcanics), acid to intermediate flows, conglomerates, and agglomerates, was formed.

The rocks of this area were then intruded by basic dikes and stocks, folded, faulted, and later intruded by granites. Erosion, intrusion of diabase dikes, and more erosion followed. During Pleistocene time the area was partly covered by glacial deposits.

[8] Moore, "Lake Savant Area, District of Thunder Bay," *loc. cit.*

[9] In this paper "iron formation" refers to particular laminae, bands, or lenses in which magnetite forms an essential portion of the rock, whereas "iron-bearing formation" refers to rock made up in part of iron formation.

[10] Graywackes in the Savant Lake area contain a high percentage of grains derived from acid to intermediate fine-grained flows.

TABLE I

STRATIGRAPHIC SUCCESSION IN THE SAVANT LAKE AREA

Formation			Character	Thickness* in Feet
Pleistocene and Recent			Drift, glacio-fluvial deposits, peat	
Unconformity				
Keweenawan (?)			Diabase dikes	
Acid intrusives			Granite, porphyritic granite, acid dikes, aplite, etc.	
Basic intrusives			Diorite and meta-diorite dikes and plutonics	
Handy Lake volcanics			Tuff, agglomerate, rhyolite, dacite, porphyry, graywacke, arkosite, conglomerate	10,000
Unconformity (?)				
Savant Series	Upper	Upper graywacke member	Graywacke, slate, tuff, arkosite, grit, quartzite	3,000
		Upper iron-bearing member	Graywacke, arkosite, iron formation, argillite	1,000
		Lower graywacke member	Mainly banded graywacke, and argillite with some arkosite	3,000
		Unconformity (?)		
		Lower iron-bearing member	Graywacke, arkosite, iron formation, argillite, quartzite, grit, tuff, conglomerate	2,000
	Lower	Upper conglomerate member	Boulder, cobble, and pebble conglomerate, graywacke, tuff, arkosite. No granite boulders	8,000
		Lower conglomerate member	Boulder, cobble, and pebble conglomerate, graywacke, arkosite. Granite boulders common	1,000
Unconformity				
Jutten volcanics			Basic and intermediate lavas predominant, iron formation, agglomerate, tuff, conglomerate, graywacke, rhyolite	17,000

* Thickness based on measurement across the strike on beds dipping at about 90°. (No repetition by folding or faulting observed.)

JUTTEN VOLCANICS

The Jutten volcanics are widely exposed in an area southeast of Savant Lake and in an area north of Kashaweogama Lake (Fig. 2). A great variety of rock types is present. Most common are basic and intermediate lavas which commonly show ellipsoidal or pillow structure. Interbedded with these rocks, which are estimated to make up more than 85 per cent of the entire formation, are more acid lavas, agglomerates, tuffs, conglomerates, graywackes, and iron formation. Some porphyritic basic and intermediate rocks are probably sill-, stock-, or dike-like intrusives into the lavas. The rocks have been altered to some extent, and in some places they have been rendered extremely schistose by shearing.

It has been common practice to combine all of these types of rocks and their metamorphic equivalents under the loose term "greenstone" and to assign them without other evidence to the Keewatin period. The Jutten volcanics are of the "Keewatin" type; and, since practically every report on the pre-Cambrian shield contains a more or less detailed description of such series, it seems unnecessary to do more than point out the similarity and to refer to the best petrographic descriptions in the literature.[11]

Structure of the Jutten volcanics.—The writer used the shapes of the pillow structures for determining tops and bottoms of flows and found that the results obtained were very consistent. In the southeast band of the Jutten volcanics, twenty-eight determinations scattered throughout the area of outcrop showed the tops of the flows to be northwest in every instance. Two determinations in which the contacts between flows were observed also showed top to the northwest. Determinations could not be made on many outcrops, owing to the small area of exposure, distortion due to folding or shearing, or indeterminate shape. No outcrop in which the shape was satisfactory for purposes of determination showed the top of the beds to the southeast. The evidence of the pillow lavas shows that the Jutten volcanics in this area form a monoclinal structure with the basal part of the formation to the southeast.

[11] Moore, "Lake Savant Area, District of Thunder Bay," *loc. cit.*, pp. 57–60; C. R. Van Hise and W. S. Bayley, "The Marquette Iron-bearing District of Michigan," *U.S. Geol. Surv. Mono. 27* (1897), pp. 490–517; A. C. Lawson, "The Archean Geology of Rainy Lake, Restudied," *Can. Geol. Surv. Mem. 40* (1913), pp. 45–50.

In the area of Jutten volcanics north of Kashaweogama Lake pillow lavas are also abundant. Six determinations made during two traverses across the strike of these greenstones all show tops of the flows to the northwest. This attitude was the opposite from that expected; and determinations were made with very great care, none being accepted unless independent conclusions by the writer and his assistant were in agreement. These observations, together with other evidence, suggests the existence of a fault contact with the conglomerate of the Savant series (p. 476). The Jutten volcanics north of Kashaweogama Lake, therefore, form a monoclinal structure striking N. 55° E., with the top of the flows to the north.

If these interpretations of the structure of the volcanics are correct, the formation, measured along a line normal to the strike of the beds from MacNamara Point to the contact with the Jutten Lake batholith, has an apparent thickness of approximately 13,000 feet. Three miles to the north measurement normal to the strike gives an apparent thickness of approximately 17,000 feet. North of Kashaweogama Lake the thickness is about 16,000 feet. In all three cases the total thickness was not determinable because both the top and the base of the formation have been removed by erosion, faulting, or granitic intrusion. There may be some duplication of beds by faulting, but there can be no duplication due to folding.

LOWER SAVANT SERIES

LOWER CONGLOMERATE MEMBER

The lower conglomerate member is best exposed on the north side of MacNamara Point. Along the shore is an almost continuous exposure of conglomerate which shows the rounded granite boulders characteristic of this member. Measured across the strike the thickness is between 600 and 700 feet. This outcrop forms the most northerly exposure of the lower conglomerate member in the southeastern portion of the map area. For, on the north shore of Stillar's Bay, less than a thousand feet away and directly in strike line, the conglomerate is very schistose and of entirely different character, belonging to the upper conglomerate member, the lower conglomerate member apparently being faulted out by an east-west fault of considerable magnitude (p. 477). From MacNamara Point the lower conglomerate has been traced southwest along the South Arm, along

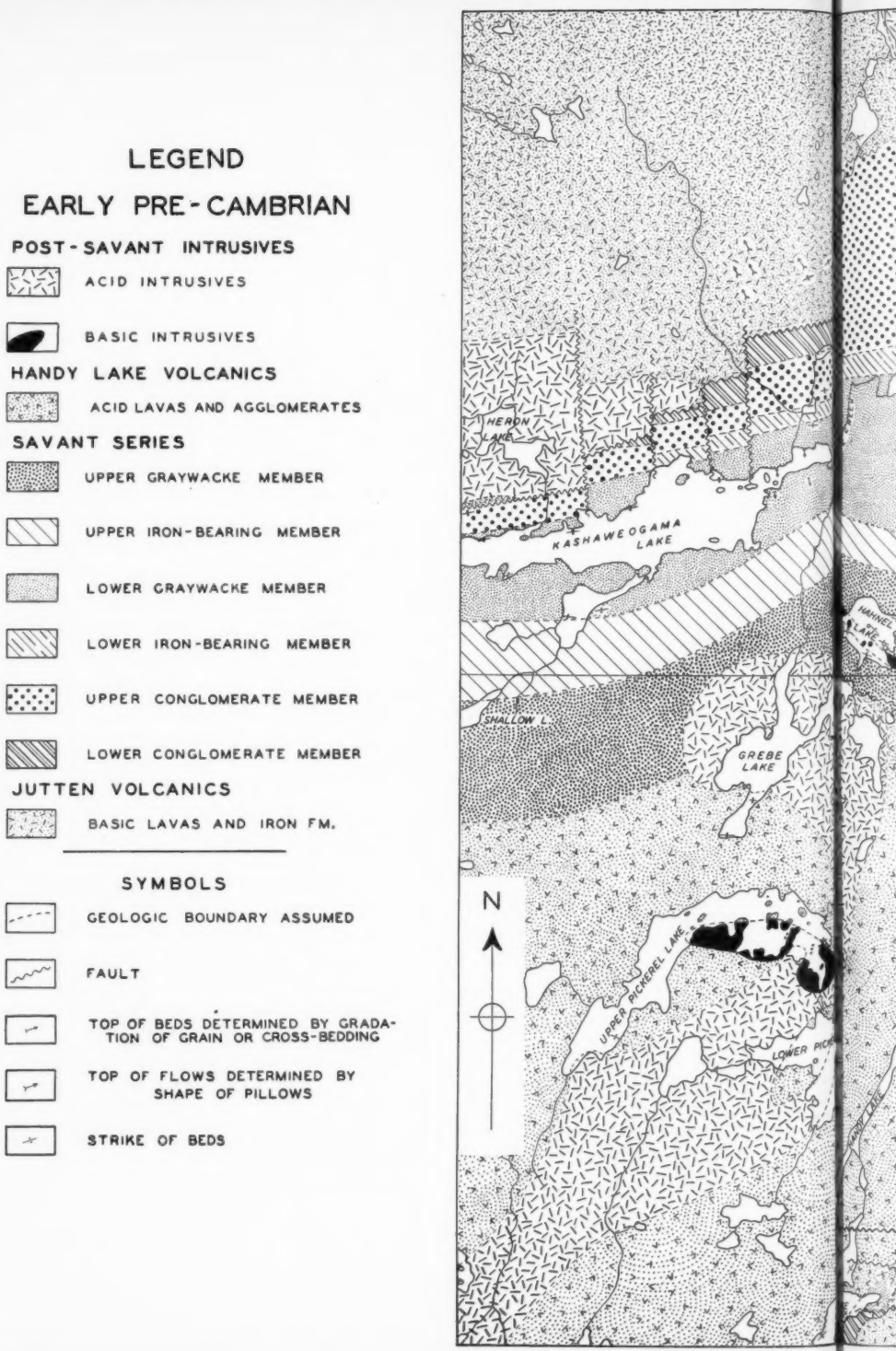
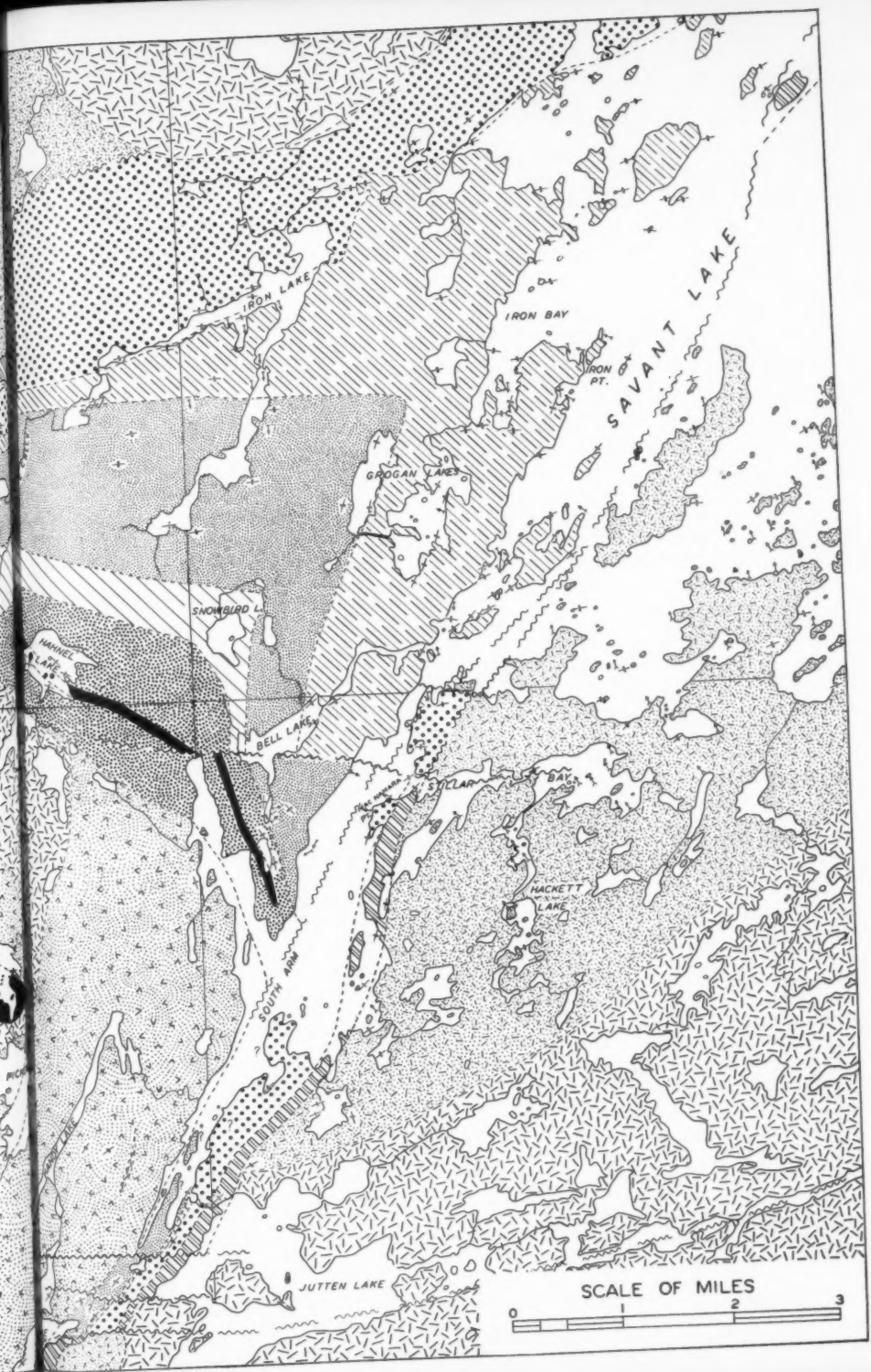


FIG. 2.—Geologic map [illegible] Lake a



map of Lake area, Ontario

the west shore of Jutten Lake, to the place where it leaves the map area east of Harold Lake.

A second band of conglomerate belonging to this lower member is found north of Kashaweogama Lake. On the east the band probably ends against the largest cross fault (p. 477). From here the belt trends west and slightly south, is offset by several cross faults, and narrows rapidly, disappearing entirely just east of Heron Lake. A part of the reduction in thickness is due to faulting.

Petrography.—The lower conglomerate member is very uniform in character. In it occur boulders, cobbles, and pebbles of granite, feldspar- and quartz-porphyries (forming not more than 35 per cent of the rock), and greenstones of various sorts. A few cobbles of vein quartz, hematite or limonite, and siliceous rock resembling jasper were found. Granite boulders up to 25 inches in diameter and greenstone boulders up to 15 inches in length were noted. Fragments of the light-colored rocks are well rounded, but the greenstone fragments, where distinguishable, tend to be lens-shaped, and where the formation is schistose are greatly elongated, whereas the leucocratic rocks are much less deformed. In the field the matrix appeared to be mainly fine-grained graywacke, though where the lower conglomerate member outcrops on Jutten Lake the matrix is more arkosic but does not seem to show any evidence of metamorphism due to the nearby granite.

Relation to underlying formation.—Direct observation of the relation of the Savant series to the Jutten volcanic[12] is rarely possible. The contact between them was observed at only one point, namely, in the southernmost exposures on the South Arm. A grayish, schistose rock intervenes; and as the conglomerate is approached, an occasional boulder may be seen. This belt of nondescript rock may represent a pre-conglomerate soil upon the greenstone. A similar occurrence has been described by Pettijohn from the Sioux Lookout area.[13]

Since granites are thought to be intruded under a minimum cover

[12] Timiskaming-Keewatin boundary of Moore. Interpreted as disconformity by him in 1931.

[13] F. J. Pettijohn, "The Conglomerate of Abram Lake, Ontario, and Its Extensions," unpublished manuscript (1930), p. 121.

of 2,500 feet and since granite boulders occur in the basal phase of the conglomerate, it seems likely that removal of at least 2,500 feet of material must have taken place before granite boulders would have been available for formation of the conglomerate. If the granite was pre-Jutten in age, probably an even greater amount of material was removed.

Further evidence of a significant break is furnished by the discordance of strike between the greenstone and conglomerate east of the South Arm. The strike of the conglomerate is approximately N. 20° E., whereas the greenstones of that area strike approximately N. 55° E. No positive evidence of faulting along this contact was observed. The simplest explanation calls for tilting and erosion of the greenstones before the deposition of the conglomerate. The amount of erosion required would have been great.

Conditions of deposition.—The lower conglomerate member is usually over 600 feet in thickness but in some places may be two or three times as thick. The rock is characteristically a boulder conglomerate with but few interbedded finer-grained layers. The boulders are exceptionally well rounded and do not show any evidence of glacial origin. The only environment in which such conglomerates are deposited today is at the foot of high mountains, as alluvial and piedmont deposits. Pettijohn[14] and others have suggested this method of formation for thick pre-Cambrian conglomerates, and the conglomerate of the Savant series appears to be of the same type and to have formed under similar conditions.

UPPER CONGLOMERATE MEMBER

The most extensive band of the upper conglomerate member extends from the west boundary of the map area, just north of Kashaweogama Lake, east and a little north for a distance of 10 miles until it leaves the area just west of Savant Lake. This band is very persistent, though cut by numerous north-south faults and intruded by the porphyritic granite north of Iron Lake. It shows great variation in thickness. North of Wiggle Creek it is approximately 8,000 feet in thickness; north of Iron Lake the thickness is not less than 6,500

[14] F. J. Pettijohn, "Conglomerate of Abram Lake, Ontario, and Its Extensions," *Geol. Soc. Amer. Bull.* 45 (1934), pp. 500–501.

feet; and east of Iron Lake the thickness exceeds 5,000 feet. West of the major cross fault north of Kashaweogama Lake the thickness is much reduced, being 2,500 feet just north of the east end of Kashaweogama Lake and less than 1,200 feet south of Heron Lake.

A second, thinner band of this upper member parallels the east shore of the South Arm from the narrows to Harold Lake (Fig. 2). On the northwest end of MacNamara Point a thickness of 700–800 feet is exposed. West of Jutten Lake, where the upper portion of the formation is dominantly arkosite, the thickness is about the same.

Petrography.—This upper member is composed predominantly of conglomerate with a variety of interbedded rock types. Near the base of the member on the second lake north of Wiggle Creek the rock is a boulder conglomerate with lens-shaped fragments of various types of felsites and porphyries up to 5×2 feet in size. The matrix, composed of finer material of the same composition, forms a minor portion of the rock. Interbedded boulder, cobble, and pebble conglomerates; arkoses; graywacke; and tuff, with the finer-grained types prominent in the upper portion, comprise the main formation. One horizon of mixed crystal and lithic tuff about 350 feet thick has been traced for about a half mile north of Iron Lake. The difficulty of differentiating between tuff and arkosite suggests that some of the beds called arkosite in the field may actually be a mixture of tuffaceous material and arkose.

The upper conglomerate is characterized by the absence of granite boulders and the predominance of material derived from acid and intermediate flows.[15] Greenstone fragments are rare except locally in the basal portion.

Conditions of deposition.—The conditions of deposition of the upper conglomerate member were probably very similar to those under which the lower conglomerate member was deposited, i.e., terrestrial accumulation in alluvial fans and other piedmont gravels adjacent to an area of strong relief. But the extreme thickness of the deposit and the composition of the detrital material derived from the adjacent high land indicates a change of conditions in that area. Granite and greenstone areas which had furnished detrital material to the

[15] The porphyry fragments rarely carry quartz phenocrysts, eight thin-sections showing only one grain of quartz in either pebbles or matrix.

lower conglomerate member no longer supplied that material but instead furnished great volumes of rock of extrusive origin. Initiation of volcanic activity in the adjacent high lands, resulting in complete blanketing of the existing terrain, would not only explain the absence of granite and greenstone boulders but would also furnish the necessary extrusive rock fragments. The horizon of mixed tuff not only substantiates the hypothesis of volcanic activity but indicates that such action continued, at least intermittently, throughout the period of conglomerate deposition. The acid character of the extruded material, the fact that the conglomerates must have formed close to the highland but were not covered by the flows, and the great variation in thickness of the conglomerate suggests that the volcanic action was of the "mountain range" type.

UPPER SAVANT SERIES

Lying stratigraphically above the conglomerate is a thick series of fine-grained sediments which may be divided on the basis of lithology into a lower iron-bearing member, a lower graywacke member, an upper iron-bearing member, and an upper graywacke member. To facilitate petrographic description and discussion of conditions of deposition these four members have been grouped together.

The inferred distribution of these members is shown on the accompanying map. Where the upper iron-bearing member is missing, it is impossible to differentiate between the two graywacke members; and in these areas the rock has been mapped as undifferentiated Upper Savant series (Fig. 2). The estimates of thickness of these members are given in the stratigraphic column (Table I) and are probably subject to considerable correction but are believed to be of the right order of magnitude.

Petrography.—The sedimentary character of the major portion of the fine-grained sediments of the Savant series is everywhere quite apparent. The rocks exhibit a distinctly banded character owing to differences in color, and this banding has been accentuated by differential weathering which has given the rock a "ribbed" appearance on the weathered surface. Closer inspection shows the sediments to be composed of a variety of rock types, interbedded in bands which vary from a fraction of an inch to several feet in width. The differ-

ences in color between the layers are due to variations in composition and grain size. The subdivision of the finer sediments into members is based on the presence or absence of iron formation. With the exception of this material the four members are very similar petrographically.

They are characteristically composed of alternating layers of graywacke and argillite with some interbedded arkosite, quartzite, and slate. In places cobble and pebble conglomerate and grit bands occur at or near the base of the lower iron-bearing member. Gradation between bands and delicate lamination within the wider bands, especially in the iron formation, were observed. The magnetite-rich bands tend, however, to be sharply defined from the other sedimentary types, although two outcrops were discovered in which the magnetite-rich bands occurred as the top member of varvelike bands. These showed perfect gradation from graywacke, through argillite, to iron formation.

Under the microscope the coarser-grained phases were seen to be arkosite, graywacke, and tuffaceous graywacke, all showing some degree of metamorphism, but none so highly altered that the primary clastic textures were completely obliterated. The suite of mineral and rock fragments in the various types is very similar, the major difference being the proportion of the different constituents present. The rounded to subangular character shown by all grains indicates a sedimentary origin. The tuffaceous graywacke shows an admixture of more angular fragments and crystals which seem to have suffered very little, if any, transportation. These coarse-grained sediments, especially the graywackes and tuffaceous graywackes, are peculiar in that they contain a very high percentage of grains apparently derived from acid or intermediate flow rocks. The quartz, generally small in amount, is mostly present as a constituent of rock fragments rather than as separate mineral grains. This deficiency in quartz and the flood of acid or intermediate flow fragments would be expected from erosion of the volcanic terrain (or from direct volcanic contribution), which was apparently the source for the upper conglomerate member.

The rather subordinate matrix of the coarser clastics, probably originally of similar composition, is now recrystallized to a fine-

grained mosaic of chlorite or biotite, quartz, and feldspar. Magnetite occurs as scattered euhedral to subhedral metacrysts intermediate in size between the grains and the matrix. In two thin sections of graywacke some of the euhedral magnetite crystals lie half in the matrix and half in the sand grains, proving their later origin. Much smaller grains are concentrated in certain areas in the matrix. Occasional grains of euhedral tourmaline were also found.

The finer-grained rocks include argillite, tuffaceous argillite, and slate. The original textures of these rocks have been largely destroyed by recrystallization, but under the microscope the original bedded character usually can be inferred from the banding of the recrystallization minerals and from occasional coarser grains, obviously sedimentary. In the argillites are quartz, feldspar, magnetite, chlorite, sericite, biotite, carbonate, hematite, and tourmaline. There is some parallelism of the biotite, chlorite, and sericite. Tourmaline, which occurs as tiny, elongated, unfractured prisms, cuts across the schistosity. One thin section from the rhythmically banded iron-bearing formation on Iron Point, Savant Lake (lower iron-bearing member), shows more than twenty crystals in a medium-power microscopic field. The size and shape of these are such that they could not have been detrital and must, therefore, have been introduced. The unfractured character of the majority of the tourmaline crystals and their orientation transverse to the schistosity strongly supports the suggestion that their formation followed the folding of the sediments.

Magnetite was seen in small euhedral crystals scattered through the argillite and as relatively large metacrysts. The latter are commonly surrounded by an area, roughly proportional in diameter to the diameter of the magnetite crystals, in which there is a deficiency of biotite and chlorite compared to the surrounding rock.

The magnetite-rich bands of the iron-bearing members are composed of interstratified laminae of fine-grained quartz and magnetite. These laminae often show excellent gradation from one to another. The magnetite-rich portions of the rock are also rich in amphibole. Study of the polished sections shows some hematite intergrown with the magnetite. Slight gradation in the size of the quartz grains within the quartz laminae suggests that there was an original

textural difference in different parts of the quartz-rich laminae. This would be difficult to explain if the quartz was originally deposited as a chert.

Within the Upper Savant series are several minor units which deserve mention. Well up in the lower iron-bearing member is a bed of mixed trachyte tuff about 600 feet in thickness. In the lower graywacke member a dioritic flow or flows about 400 feet in thickness, underlain by a mixed andesite tuff of about the same thickness, was observed on the north shore of Kashaweogama Lake. Occurring also in the lower graywacke member is a little boulder conglomerate in bands, varying from about 100 feet in thickness east of Grebe Lake to about 25 feet in thickness on the south shore of Kashaweogama Lake. No granite boulders were identified. In the same member on the east shore of Iron Lake is an excellent exposure of arkosite which shows cut and fill structure and cross-bedding.

Conditions of deposition.—The sediments are well sorted, occur in persistent narrow bands which commonly show gradation from sandy material to silt and clay, and show little evidence of chemical alteration before deposition. They are underlain by thick conglomerates which are interpreted as continental deposits. The character of the sediments, with the exception of the iron formation, and their relation to the underlying thick conglomerates is very similar to that found in the Sioux Lookout area, about which Pettijohn says:

> The upper part of the Abram series differs from the lower part in that it shows a greater lithologic diversity, different sedimentary structures, better sorting and scarcity or absence of larger fragments. In view of the probable continental origin of the conglomerate beds of the lower formation and of the characteristics of the Abram graywackes and slates, it is likely that the latter were deposited in fresh waters and that the cyclic alternation of types corresponds to periodic flooding, perhaps annual, of the area. The deposits of clay, silt, and impure arkosic sands alternate with great frequency, with seasonal changes. The deposits being continental, there is an absence or scarcity of limestone. . . . . In so far as pyroclastic rocks occur they represent a contamination of flood plain deposits. The incomplete weathering and sorting of the graywackes and arkosites and the variability of the section would be more consistent with fresh water and continental origin than with marine origin.[16]

[16] "Conglomerate of Abram Lake, Ontario, and Its Extensions," *Geol. Soc. Amer. Bull. 45* (1934), p. 501.

Allowing for the derivation of sediments in the Savant area from a source which furnished dominantly acid and intermediate volcanic material as reflected in the peculiar composition of the graywackes and the scarcity of true arkosite and quartzite, it is very probable that the sediments of the Savant Lake area were deposited under essentially the same conditions as those in the Sioux Lookout area.

In the preceding portions of this paper it has been assumed that the ferruginous material of the iron formation was in the sediments in which it is now found at the time of, or soon after, their deposition. On this assumption the finer-grained sediments of the Savant series were subdivided into four members on the basis of presence or absence of iron formation. There is evidence, however, which suggests the possibility of introduction of the ferruginous material long after the deposition of the sediments through selective replacement by hydrothermal solutions.

The possible epigenetic origin of the iron formation is most strongly suggested by the microscopic examination. The presence of considerable introduced, unfractured tourmaline in the clastics, especially the argillite, implies the circulation of hydrothermal or pneumatolitic solutions through the rocks subsequent to their deformation. Original clastic structures truncated by magnetite metacrysts show that some movement of the ferruginous material took place subsequent to deposition. The siliceous character of the iron formation, when contrasted with the deficiency of quartz in the interbedded sediments, might be the result of epigenetic introduction of the silica. The great apparent thickness of the lower iron-bearing member off the nose of the Grebe–Pickerel Lake granite is also suggestive, thought it might be explained equally well by an unconformity between the lower iron-bearing member and the overlying graywacke member. These four points, namely, the presence of hydrothermal solutions, some movement of the ferruginous material, high silica content, and areal distribution, do no more than suggest the possibility of epigenetic introduction of the iron.

On the other hand, it has been shown that the distribution of the iron formation is such that it composes two mappable units, an upper and a lower iron-bearing member separated by a non–iron-bearing graywacke member. This limitation of the iron formation to

specific stratigraphic horizons, coupled with the petrographic similarity of the clastic material of all of the finer-grained sediments (and, therefore, their equal opportunity for replacement if such replacement took place) and the delicate, persistent, interbedded character of the iron formation, is strongly suggestive of syngenetic origin.

If the iron formation is a syngenetic deposit, as seems most likely, there are several features which merit further discussion. Moore has noted that the iron formation is closely associated with igneous rocks. The writer has been unable to locate the interbedded flows described by Moore,[17] but does recognize not only the existence of tuffs but also the peculiar, quartz-deficient character of the interbedded graywacke. The ferruginous material, if not derived from volcanic emanations, was probably furnished by the disintegration of acid to intermediate rocks.

Moore and Maynard[18] show that electrolytes, present in the concentrations found in sea water, and certain types of bacteria are effective in precipitation and deposition of iron. It should be noted, however, that the sediments of the Savant Lake area are probably of fresh-water origin. Furthermore, the iron formation was formed as the upper member of varvelike couplets which show perfect gradation from graywacke, through argillite, to iron formation. Sauramo[19] has shown that under present conditions varved structures showing gradation of grain do not form in salt water due to flocculation of the finer constituents by electrolytes. Therefore it is doubtful whether the Savant iron formation was formed through precipitation by electrolytes in sea water. On the other hand, no remnants of organic structures have been found.

It would be possible, however, to have the iron precipitated by electrolytes in lacustrine deposits through recurrent (perhaps seasonal) evaporation of the fresh-water lakes in which the sediments were deposited. During the greater part of the cycle the water

[17] "Lake Savant Area, District of Thunder Bay," *loc. cit.*, p. 82.

[18] E. S. Moore and J. E. Maynard, "Solution, Transportation and Precipitation of Iron and Silica," *Econ. Geol.*, Vol. XXIV (1929), pp. 277–79.

[19] Matti Sauramo, "Studies in the Quaternary Varved Sediments in Southern Finland," *Bull. Comm. Geol. Finlande*, Vol. LX (1923), pp. 91–98.

would be fresh, and ordinary varved structures might be formed; but as concentration occurred, the iron might be precipitated during the later stages of the cycle.

HANDY LAKE VOLCANICS

Distribution and thickness.—Lying stratigraphically above the upper graywacke member and forming the center of the Savant synclinorium is a very thick series of tuffs, agglomerate, porphyritic rhyolite, rhyolite, other acidic volcanic rocks and conglomerates, grits, and finer-grained sediments derived from them, which are grouped together and distinguished as the Handy Lake volcanics. This series is best exposed between the South Arm of Savant Lake and Lower Pickerel Lake, where the volcanics have an estimated thickness of 10,000 feet. From the data available at present the formation seems to be divisible into a basal tuff which grades up into a member composed dominantly of porphyritic rhyolite. Above, and perhaps in part contemporaneous with this flow member, is a member composed dominantly of conglomerate and agglomerate apparently derived from the underlying material in large part.

The lower tuff member is best exposed between the South Arm and the west line of Jutten Township. It is schistose and appears more highly weathered than most sedimentary rocks of the area. The middle flow member is typically exposed between Handy and Lower Pickerel lakes and has been studied in some detail by Moore,[20] who found that the rocks along the portage between the two lakes vary from porphyritic rhyolite to dacite. Study of a series of thin sections collected along the same portage by the writer confirms Moore's work.

The agglomerates and conglomerates of the Handy Lake volcanics appear to have a very erratic distribution. They are best exposed on Grebe and Upper Pickerel lakes, where they appear as bedded deposits interstratified with arkosite, graywacke, and grit. This member apparently continues westward.[21]

The contact between the Handy Lake volcanics and the upper graywacke member may be observed along the west end of the

[20] "Lake Savant Area, Thunder Bay District," *loc. cit.*, p. 63.

[21] *Ibid.*, p. 63.

Grebe–Savant Lake portage. There is no pronounced angular unconformity between them at this point. In the southern part of the map area the Savant series is greatly reduced in thickness and the basal contact of the volcanics appears to be transgressive. Until the structural relations, particularly the faulting, have been worked out in greater detail, it is impossible to determine the magnitude of any unconformity that may exist.

BASIC INTRUSIVES

Basic dikes and small intrusions of diorite and metadiorite were found. The largest area of metadiorite occurs on the east end of Upper Pickerel Lake as a triangularly shaped mass about $1\frac{1}{2}$ miles long and less than $\frac{1}{2}$ mile wide at the east end. Near the granite it is a coarse-grained, massive, granitoid, dioritic-appearing rock, but farther from the granite it is less metamorphosed. Under the microscope its original dioritic character is quite apparent.[22]

As noted on page 466, the mass of diorite forming a portion of the north shore of Kashaweogama Lake is thought to be extrusive rather than intrusive. The intimate association of the diorite with basic tuffs, the elongated, narrow outcrop of the diorite, and the discovery of structure suggestive of ellipsoids, form the evidence for the change in interpretation.

Several large basic dikes and numerous small dikes were mapped. In most cases the dike relation was clear, either because of cross-cutting relation to the intruded beds, because of narrow widths, or because of coarseness of grain at both contacts.[23]

The time of intrusion of most of the basic rocks can be definitely determined. Those intruded into the Savant series must be post-Savant series in age. Those cut by quartz veins are probably pre-granite in age. This post-sedimentary, pre-granite age relation has

[22] A portion of this mass was mapped as Keewatin, a part as sedimentary, by Moore (1928).

[23] One dike located on an island in the extreme northeastern corner of the map area is of particular interest due to the inclusion of a number of cobbles and pebbles of granite and vein quartz and a large amount of rounded, unassimilated silicic material of sand size. The included material appears to be derived from the conglomerate which underlies the sediments into which the dike was intruded.

been found in other areas in northwestern Ontario; and the rocks are referred to as "Haileyburian" by Watson.[24]

ACID INTRUSIVES

With the exception of the area north of Kashaweogama and Iron lakes, granite and porphyritic granite were found to have essentially the area distribution shown by Moore.[25] North of Kashaweogama and Iron lakes, however, the granitic intrusives are much less extensive than formerly mapped and are limited to a small stock near Heron Lake and a stock or border of a batholith north of Iron Lake, the rest of the area formerly mapped as granite being greenstone and conglomerate. A small number of dikes of granite, aplite, and rhyolite-porphyry were also found.

The petrographic study of the granitic rocks, though limited to a few thin sections from each mass, shows differences in texture, mineral assemblages, and degree of shearing and fracturing sufficient to characterize each mass, at least in the area studied. The porphyritic mass north of Iron Lake is characterized by its fresh and massive appearance and by the very large euhedral phenocrysts of pink orthoclase which average about $1\frac{1}{2}$ inches in length.[26] The Grebe–Pickerel Lake stock appears to be almost identical in mineral assemblage, degree of shearing, and alteration with the Iron Lake mass, but is not porphyritic. Locally it is more highly sheared. The Heron Lake mass may be distinguished from the other granites by the extreme alteration of the feldspars and by the microscopic augen structure with quartz as the interaugen material. The Jutten Lake granite is characterized by the extreme granulation of the essential miner-

[24] R. J. Watson, "Platinum-bearing Nickel-Copper Deposit on Lower Shebandowan Lake, District of Thunder Bay," *Ont. Dept. Mines*, Vol. XXXVII, Part IV (1928), pp. 133–34.

[25] "Lake Savant Area, District of Thunder Bay," *op. cit.*, pp. 53–82.

[26] Of special interest in this mass is the variation in the development of the large orthoclase phenocrysts near the contact with conglomerate on the little lake north of Iron Lake. Dikes up to four inches in width have no phenocrysts. As the width of the dike increases, the phenocrysts increase in size until above an eight-foot width the phenocrysts are about an inch in length. This relation seems to indicate that the magma was in a very fluid condition with few crystals and no phenocrysts at the time of its intrusion. The granite, however, produced very little alteration in the conglomerate, pebbles and cobbles being readily distinguishable a few inches from the contact.

als and can be differentiated from the other granitic rocks of the map area by this characteristic and its darker color in the hand specimen. These suggested differences are, of course, tentative; and petrographic study of larger suites of samples, perhaps supplemented by a study of the heavy accessory minerals, should be made.

As pointed out by Moore, granites of two quite different ages have existed in this portion of northwestern Ontario. Granite boulders in the lower conglomerate member of the Savant series must have been derived from a granite older than that series. The Grebe–Pickerel Lake stock and the porphyritic granite north of Iron Lake are definitely intrusive into the Savant series and are, therefore, younger granites. Both the Heron and Jutten Lake masses are intrusive into the Jutten volcanics, but the relation to the Savant series was not sufficiently clear to warrant their unreserved classification as younger granites. Because of Moore's classification of them as later than the Savant series and for lack of conclusive evidence of earlier origin they are here tentatively correlated and mapped as younger granites.

KEWEENAWAN (?)

In his study of the Savant Lake area Moore found basic dikes cutting the granites and referred them to the Keweenawan.[27] All basic dikes found by the writer in the map area either are cut by quartz veins and are, therefore, probably younger than the granites, or are not associated with such veins. But on a reconnaissance trip north on Savant Lake one large diabase dike was found cutting across the quartz veins and was, therefore, probably post-granite. It is possible that basic dikes of this area may be discovered within the limits of the map area.

PLEISTOCENE AND RECENT

Deposits of glacial origin are widely distributed. They occur mainly as fillings of basins of the bedrock surface, but in several places, namely, between Jutten and Savant lakes, south of Kashaweogama Lake and north of Iron Lake, form well-defined ridges, probably moraines. The drift has been more fully described by Moore.[28]

[27] "Lake Savant Area, District of Thunder Bay," *loc. cit.*, p. 65.

[28] *Ibid.*, p. 65.

CORRELATION

The custom of students of the pre-Cambrian of northwestern Ontario is to correlate the rocks of the various "schist belts" on the basis of lithology, stratigraphic sequence, and the relation of the extrusive rocks and the sediments to the granitic intrusives. Nearly all of the greenstones have been called Keewatin; and when overlying sedimentary beds are present, they have been correlated with the Timiskaming. Granites which intrude the sediments are called Algoman. In many cases no evidence is given for such correlation, and in most other cases the evidence which is presented does not warrant the conclusions derived from it. About twenty-five years ago these same rocks were correlated unhesitatingly with the Keewatin, Huronian, and Laurentian.

The rocks of the Savant Lake area were correlated with the Keewatin, Huronian, and Laurentian up to 1928 by all geologists who worked in the area. In 1928 Moore stated in regard to the granitic intrusives:

> . . . . there is no way of determining the true age of this granite at present, but it seems probable that it may be Algoman. . . . . In the earlier report, mentioned above [1910], the granite and granite gneiss were mapped as Laurentian according to the custom of the day among many geologists.[29]

Concerning the correlation of the greenstones and sediments, he noted:

> Following the ordinary procedure in classifying formations according to age, the main conglomerate should be considered as indicating a great unconformity and, together with the younger associated rocks, as belonging to the Timiskaming or some age other than Keewatin.[30]

In 1929 the same writer[31] definitely correlated the sediments of the Savant Lake area with the Timiskaming on three kinds of evidence, namely, high degree of folding, presence of a prominent basal conglomerate containing boulders and pebbles of granite, and varve-like banding of the sediments. The correlation may be correct, but the writer prefers to use local names until such time as general names can be applied with more certainty.

[29] *Ibid.*, p. 64. [30] *Ibid.*, p. 57.

[31] E. S. Moore, "Keewatin-Timiskaming Boundary," *Geol. Soc. Amer. Bull. 40* (1929), pp. 547–56.

There are two areas, however, with which some comparisons may reasonably be made, the Sioux Lookout area, which lies about 75 miles to the west, and the Sturgeon Lake area, which is about 30 miles to the south. The former area has been extensively studied during the last seven years by Pettijohn,[32] who found a thick series of greenstones, overlain unconformably by thick conglomerate and arkose. This, in turn, is overlain by a series of banded fine-grained sediments interbedded with some pyroclastics and perhaps some volcanics. Above this dominantly sedimentary sequence is a thick series of pyroclastics and volcanics of unknown thickness. Reference to the accompanying correlation chart shows that there is apparently a marked similarity between the larger units of the Savant Lake and Sioux Lookout areas, but in detail the relationships are less clear.

In the Sturgeon Lake area less detailed work has been done. Sediments have a limited distribution, as has a band of rhyolite and pyroclastics. The former may be the time equivalent of the Savant and Abram conglomerates; the latter may be the equivalent of the Handy Lake volcanics or perhaps the Patara series.

Structural Geology

General Statement

The structural geology of the Savant Lake area is very complex. That the area is a portion of a great synclinorium was recognized by Moore,[33] but that those intensely folded rocks were also cut by numerous faults of great displacement was not considered probable by him. The writer proposes to review briefly the evidence for folding and then to discuss the evidence for five of the most important faults. The faults that have been found and described are important, but it is believed that several more of similar or greater magnitude will probably be found.

Folding

Moore's conception of a central mass of fine-grained sediments, volcanics, and pyroclastics flanked by two converging bands of conglomerate, and these in turn flanked by areas of greenstones, must be

[32] "Conglomerate of Abram Lake, Ontario, and Its Extensions," *Geol. Soc. Amer. Bull. 45* (1934), pp. 479–506.

[33] "Lake Savant Area, District of Thunder Bay," *loc. cit.*, pp. 65–66.

TABLE II

CORRELATION OF THE SAVANT LAKE AREA WITH THE SIOUX LOOKOUT AND STURGEON LAKE AREAS

Savant Lake Area			Sioux Lookout Area*		Sturgeon Lake Area
Pleistocene			Pleistocene		Pleistocene
Unconformity			Unconformity		Unconformity
Keweenawan (?)					
Unconformity					
Granitic intrusives			Granitic and basic intrusives		Granitic and pregranitic intrusives
Basic intrusives					
Handy Lake volcanics			Neepawa volcanics (tuffs and flows)†		Basic volcanics (?)‡
Unconformity (?)			Unconformity (?)		Unconformity (?)
Savant Series	Upper	Upper graywacke member	Abram Series	Daredevil formation (iron formation, interbedded sediments and tuffs)	
		Upper iron-bearing member			
		Lower graywacke member			
		Lower iron-bearing member			
	Lower	Upper conglomerate member		Ament Bay formation (conglomerate and arkosite)	Conglomerate and graywacke§
		Lower conglomerate member			
Unconformity			Unconformity		Unconformity (?)
Intrusives (?) (granite pebbles in conglomerate)			Intrusives (quartz-porphyry, metadiabase and metadiorite. Granite pebbles in conglomerate)		Intrusives (?) (granite pebbles in conglomerate)
Jutten volcanics			Gray "greenstone"		Basic volcanics (?)‡
			Patara series‖		
			Green "greenstone"		

* Specifically Vermilion Township.
† East Bay, Minnitaki Lake.
‡ Assigned to "Keewatin" by Graham, but may be of two ages as indicated.
§ Not confirmed by Tanton. ‖ This series mapped by Hurst as Temiskaming conglomerate.

somewhat modified in the light of the writer's work, but, nevertheless, is probably essentially correct. The tops of the Jutten volcanics north of Kashaweogama Lake face away from, not toward, the axis of the synclinorium. There is strong evidence that the contact of these beds with the conglomerate to the south is a fault contact. Determination of top of beds by gradation of grain, cross-bedding, and cut-and-fill structures indicates that the top of the conglomerate, as well as that of the finer-grained sediments to the south of the conglomerate, does face the center of the synclinorium.

On the South Arm, the tops of the Jutten volcanics all face northwest, as do the tops of the overlying conglomerates. The structure of the finer-grained sediments, however, is more difficult to interpret, especially north and west of the narrows between Savant Lake and the South Arm, where the iron-bearing members are highly contorted.

The original attitude of the sedimentary and extrusive rocks in the map area must have been very near to the horizontal. Owing to the folding of the rocks, however, they are now all essentially vertical, or, as near the South Arm, somewhat overturned. No dips less than 65° were noted at any point in the map area.

FAULTING

One of the most important faults for which there is considerable evidence separates the Jutten volcanics and the Heron Lake stock from the conglomerates north of Kashaweogama Lake and Wiggle Creek (Fig. 2). As noted above, structural determinations by means of pillow structure show the top of the greenstone to the north. Only six determinations were made, but they all agree. Near Heron Lake greenstone is intruded and considerably metamorphosed by the Heron Lake granite. The adjacent conglomerates are not cut or metamorphosed by the intrusion. The Heron Lake stock has several gneissic zones parallel to the supposed fault, and the greenstone and the granite to the north and the conglomerate to the south are everywhere separated by low ground along the line of the fault. The conglomerate shows great reduction in thickness from east to west; but it is the lower, not the upper conglomerate, that is so reduced (Fig. 2). Since the conglomerate and greenstone now lie "bottom to bottom" on opposite sides of the fault, the amount of displacement was

probably considerable. If the fault plane dips at a high angle, it is difficult to conceive how a vertical movement could result in the "bottom to bottom" relationship. For this reason it is believed that the displacement was probably horizontal.

In this same area there are several north-south cross faults which displace the strike fault mentioned above. The most important of these is located north and slightly east of Kashaweogama Lake. Four others were found between that point and the west line of the map area. All are postulated because of offset relations of the conglomerate and greenstone in this area (Fig. 1).

A second area in which faulting is prominent but in which the relations are less clear is the neighborhood of the South Arm of Savant Lake. The existence of an east-west cross fault just south of the narrows between the main lake and the South Arm is required to explain the sudden ending of the iron-bearing members at that place and also to explain the disappearance and change of strike of the lower conglomerate member between MacNamara Point and the north shore of Stillar's Bay.

A strike fault (northeast trend) probably follows the center of the South Arm, separates the iron-bearing member from the conglomerate at the narrows, and then forms the iron-bearing member–greenstone contact through the main lake. In the South Arm the strike of the beds on the west shore is about N. 35° W. Graded bedding indicates that the top of the beds is to the east. On MacNamara Point the conglomerate strikes N. 20° E., and the top of the beds is to the west. At the narrows the iron-bearing member, in contact with the conglomerate, strikes N. 20° E., whereas the adjacent conglomerate strikes east-west. On the main lake the iron-bearing member is highly contorted and the strike of the individual beds cannot be determined, but the conglomerate members are missing. These discordant relations strongly suggest a fault.

The eastward-striking conglomerate on the north shore of Stillar's Bay was interpreted by Moore as possibly the result of folding. Moore notes that

> . . . . the main syncline was formed first and that pressure was later applied from the north and south and that the lava flows in this zone were tipped into a vertical position and schisted, with the strike running nearly east and west.[34]

[34] *Ibid.*, p. 67.

The writer believes that this is probably a partially rotated fault block. Moore's theory would not explain the greenstone in the northern part of this area which was mapped by him as conglomerate.

Three small east-west faults south of the South Arm are indicated by the offsetting of the members of the Savant series and by the very narrow watercourses in Jutten township with which they are alined. The structure in the area north of the Iron–Savant Lake portage is still not understood. That some faulting has taken place is shown by the occurrence of conglomerate and the iron-bearing member in strike line with one another, separated by only a hundred feet or so of covered ground. That there has also been folding is shown by the folding of the iron-bearing member on the portage.

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GEOLOGIC DEDUCTIONS FROM A THERMAL EQUATION

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ABSTRACT

A thermal source is indicated for the energy of earth distortion and deformation of the outer lithosphere. Heat is available and effective for these purposes in direct proportion to the unevenness of its distribution. Radioactive elements, which are considered to be the most important source of heat in outer shells, migrate extensively in geologic time through erosion and movements of magma. An investigation of the interplay in time of the factors of thermal conductivity and vertical and horizontal distributions of radioactive elements seems to show that small fractional differences in each of these factors may decree important differences in geothermal history. Predictable effects of diversity of geothermal conditions, such as thermal distortion, magma generation, magma migration, and forceful intrusion followed by deformation, are indicated. In addition some conclusions are drawn concerning the origin of batholiths and of certain types of extrusives.

INTRODUCTION

Of all sources of energy which have been suggested to account for the earth's hypogene activities, heat alone seems to possess the necessary magnitude. Frequently recurring igneous activity suggests a continual generation of magma, unless it is assumed that there is a permanent supply. Persistent unrest in the outer earth seems to imply continual distortion of the deeper lithosphere. Diastrophic forces are expended slowly, which makes it seem probable that great quantities of energy are slowly translated into the forces which cause the deeper distortions. Considering the fact that earth materials have low thermal conductivity, it is found that the rate of heat transfer on a scale to bring about effective distortion is in reasonable agreement with the rates of diastrophic processes. Further evidence of the probable importance of heat is found in the close association throughout geologic time of intrusion and deformation. The generation of magma is a thermal process; and regions of intense deformation, the so-called "mobile belts," are conspicuously regions of excessive thermal losses.

The availability of heat for distortion depends upon effective differences of temperature from region to region. A perfectly insu-

lated earth with uniform temperature throughout and no local generation of heat would never be thermally distorted. It has been known for a long time, however, that temperatures vary in marked degree along all radii, and appeal was made in the theory of thermal contraction to this vertically uneven distribution of heat to explain the shortening of the outer shell by folding. The same theory permitted the view that variation of thermal conductivity from place to place in the heterogeneous outer shell might be important enough to lead to thermal distortion and consequent inequalities of elevation at the surface. The discovery that radiothermal energy is probably the dominant factor in determining temperatures in the outer lithosphere was very disturbing to the thermal-contraction theory. It is surprising that the same discovery did not suggest the possible importance which might be attached to a lack of uniformity in the distribution of radioactive elements as a means of inducing thermal distortion. Instead, uniformity and symmetry of distribution have been overemphasized in dealing with geothermal problems.

It is now generally admitted that radioactivity is largely confined to the outer layers of the earth, where it is the chief source of heat; but it is not clear why it has been assumed to have an even distribution around the earth. Perhaps the assumption comes from giving undue weight to the evidence of compositional zoning, but the known heterogeneity of the outer lithosphere should be very disturbing to the conception of even distribution. Also disturbing to the same assumption is the evidence that rock material in thicknesses of many thousands of feet has been removed from broad regions and deposited on others. Involved in these great transfers by the agents of erosion are thick masses of the outer parts of batholiths which are said to possess radioactive elements in relatively high concentrations. Since most continental regions have been base-leveled several times, it seems reasonable to infer that the most important source of heat for the outer lithosphere is migratory to a considerable extent. It could hardly be imagined that each migration of radioactive elements at the surface is delicately compensated by a similar transfer of these materials in deeper levels. Equally disturbing to the conception of uniform distribution is the evidence of

the wholesale migrations of magma through great distances in both vertical and horizontal directions. A migrating magma has the immediate effect of transporting important quantities of accumulated heat, but a more far-reaching and thermally disturbing effect may come from the transfer of radioactive elements incorporated in the magma. Other things being equal, it may be expected that rocks best supplied with these elements will be more likely to form magma, and therefore to migrate, than will others less well endowed with this important source of heat.

The view has already been brought forward that magma migrates horizontally in deeper levels before rising into the shallower levels of final emplacement.[1] However, even if the horizontal transfer of important quantities of radioactive elements in migrating magma is not conceded as possible, there can be no serious doubt of the disturbance to radial distribution of those elements by the vertical rise of magma. It can be shown that changes in the radial disposition of radioactive elements may disturb thermal equilibrium just as effectively as would changes in the horizontal distribution. In this connection, the evidence that the outer lithosphere is largely made up of intrusives, emplaced during successive geologic periods, is of particular significance. Furthermore, if there are acceptable foundations for the views that continents exist as such because they consist of sial of low density, and that extensive borderlands and other continental areas have given place to deep seas, it is not easy to avoid the conclusion that there have been extensive horizontal migrations of sial, and consequently of radioactive elements.

Objection may be raised to the suggestion that variations from regularity of radioactive distribution and of thermal conductivity exist and continue to exist in sufficient degree to account for earth movements. It is a matter of importance, therefore, to find out what degree of variation in these factors is needed to produce notable thermal effects. The immediate object of the present paper is to show that small fractional variations in the vertical and horizontal distributions of radioactive elements and in thermal conductivity from place to place are sufficient to cause differential thermal effects

[1] J. S. De Lury, "The Magmatic Wedge," *Amer. Jour. Sci.*, Vol. XXVIII (1934), pp. 341–52.

of great importance. To begin with, it is necessary to consider the geothermal factors and to decide which of these are of vital importance to the discussion.

GEOTHERMAL FACTORS

Of the ultimate sources of the heat which determines temperatures in various parts of the outer shells, only two seem to be important: one is the store of heat in the deep interior, which is being constantly conducted toward the surface; the other is radioactivity, which is generally considered to be largely limited to an outermost shell only a few tens of kilometers thick. An approximate estimate of the relative values of these two sources is essential to discussion of the geothermal problem.

It is held by practically all students of radioactivity in rocks that heat from this source exceeds that from other ultimate sources in determining temperatures in outer shells. Joly[2] concluded that sufficient radiothermal energy is generated to cause periodic liquefaction of a continuous and thick shell of basaltic material. His calculations were based on averages of many analyses of abundant igneous rocks and on the assumptions (1) that radioactive elements are symmetrically distributed and (2) that an average gradient depicts thermal conditions more or less closely under most regions. Holmes[3] developed the view that there may still be sufficient radioactivity at great depths to give rise to convection currents in a thick silicate shell. Jeffreys estimated that the commonly accepted average geothermal gradient of about 30° C. per kilometer is "enough to carry off the radioactive heat as fast as it is produced, and also some original heat."[4] Holmes and Jeffreys, like Joly, assumed regular distribution of radioactive elements and that an average thermal gradient holds along all radii. Willis, on the other hand, concluded that "the distribution of radioactive elements could not have been uniform, and it follows that hypotheses built upon the unreal assumption of uniformity must themselves lack reality."[5] In his latest

[2] John Joly, *The Surface-History of the Earth* (Oxford: Clarendon Press, 1925).

[3] A. Holmes, "Radioactivity and Earth Movements," *Trans. Geol. Soc. Glasgow*, Vol. XVIII, Part III (1928–29), pp. 559–606.

[4] H. Jeffreys, *The Earth* (Cambridge: University Press, 1929), p. 145.

[5] B. Willis, "Radioactivity and Theorizing," *Amer. Jour. Sci.*, Vol. XXIII (1932), p. 225.

statement Jeffreys departed somewhat from the assumption of symmetry of thermal conditions which characterized his earlier speculations, when he wrote:

> Until recently the theory of thermal contraction has always been worked out on the supposition of symmetry. There are strong reasons for believing that this is too simple, and that the cooling has varied from place to place.[6]

The great diversity shown by measured geothermal gradients definitely supports the conclusion of Willis. If, as the evidence goes to show, radioactivity is the dominant thermal factor in outer shells, it seems logical to conclude that it is the chief factor in determining the thermal gradient from place to place. It would follow, therefore, that diversity of gradient is explained chiefly by unevenness in the distribution of radioactive elements. In this connection, the lowest of the measured thermal gradients is of special interest, since it would most nearly indicate the flow of heat from the interior if there were no radioactivity to disturb that flow. Measured thermal gradients, chosen to emphasize their variation, were listed recently;[7] and the following conclusion was drawn:

> Interpretations from the low gradient support the views which were derived by others from different considerations, that radioactive material is the dominant source of heat in outer shells, that it is largely concentrated in shallow levels, and that there can be very little radiothermal activity in deeper shells.

Heat carried by migrating magma is a factor of considerable importance in determining thermal conditions in outer shells. Its effects are particularly pronounced in the mobile belts, which, however, are temporary in each of their respective locations. Magmatic heat is not considered to be one of the ultimate sources, since it probably comes indirectly from the sources already named. It is possible, moreover, because of the relative importance of radiothermal energy, that without radioactivity the earth would have no generation of magma. The importance of magma migration in the thermal history of the earth is indicated by the positive evidence that all parts of the continental lithosphere have been invaded at one time or another by magmas. In fact, the continents appear to have been built essentially by igneous processes which have accompanied a

[6] H. Jeffreys, *Earthquakes and Mountains* (London: Methuen & Co., 1935), p. 164.

[7] J. S. De Lury and H. C. Lane, "Radioactivity and Geothermal Gradients," *Pan-Amer. Geol.*, Vol. LXIV (1935), pp. 101, 105.

migrating series of mobile belts. Both vertical and horizontal migrations of magma will cause prompt and serious disturbances to local thermal gradients. These effects, however, are relatively temporary and probably less significant in an ultimate way than the effects which follow the migration of radioactive elements contained in the magma.

Many other factors which might influence the steepness of the estimated thermal gradients can be named, but their effects are probably eclipsed in a general way by the factors already enumerated. Among the factors which will be neglected in dealing with thermal conditions below the surface are surface temperature, latitude, elevation, and movements of underground water.

INTERRELATIONS OF GEOTHERMAL FACTORS

If effects of magma migration be ignored, it can be said that temperatures and changes of temperature in any portion of the outer shells are determined in the main by the generation of radioactive heat, by thermal conduction to or from the interior, and by heat lost by conduction toward the surface. For unit mass in unit time the equation,

$$Ha = Hr + He - Hc\,,$$

expresses the relation between the factors which determine the amount of heat accumulation or heat loss and, therefore, of change of temperature. In the equation, Ha is the increment of heat accumulation or, when negative, of heat loss; Hr is heat being derived from radioactive elements in the unit mass; He is the interchange of heat by conduction between the mass and the interior; and Hc is the increment of loss by conduction outward.

In the equation Hr is the only factor that does not vary materially in the course of time, except in those long intervals when a slow decay of radioactive substance becomes significant. A change in any one of the other factors will disturb all factors of the equation except Hr. Each positive increment of Ha implies a rise of temperature, with a consequent increase of Hc and decrease or increase of He. As time goes on, Ha and its corresponding increment of temperature, which are relatively large in the beginning, eventually ap-

proach zero value. However, magma may form while *Ha* is still an important quantity, and in this case the temperature increment becomes zero.

The effects of changes in the various factors of the thermal equation will be discussed with the aid of Figure 1, in which for simplicity it is assumed that radioactive material is introduced into level *D*. Thermal gradient *5* is chosen arbitrarily to represent the flow of heat from the interior as if undisturbed by radioactive

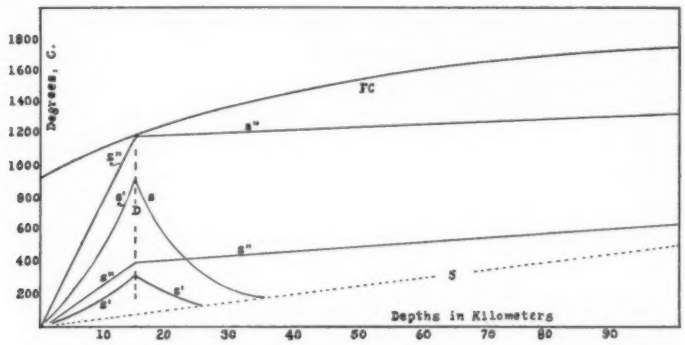

FIG. 1.—A depth-temperature diagram. *FC* represents temperatures of fusion at various depths. Radioactive material is assumed to be concentrated in level *D* in quantities sufficient in one case to require a maximum temperature of about 400°, and in another case about 1,200°. The thermal gradients, changing in each case with rising temperatures, are indicated by *s'* and *s''*. A thermal gradient of 5° per kilometer is assumed to depict the flow of heat from the interior as if there were no other disturbing source, and is indicated by *5*.

sources in outer shells. Radioactive heat is generated in level *D* and begins to disturb gradient *5*. In one case depicted in Figure 1 it is assumed that enough radioactive material is concentrated in the level *D* to give an ultimate temperature of about 400°. Temperature rises with increasing slowness to about 300°, and the corresponding thermal gradients slowly approach but never assume true rectilinearity. At 300° these gradients are depicted by *s'* above and below the level *D*. During the next stage further rise of temperature is permitted only by the slow accumulation of heat below the level *D*, as shown in the change of attitude of the thermal gradient from

s' to s''. Before the two parts of s'' can each assume rectilinearity, the factor Hr of the thermal equation is seriously disturbed by the slow waste of radioactive substance. Ha becomes negative, and temperature falls slowly. In the thermal equation during these successive stages, He begins as a positive quantity, then becomes increasingly negative, in the next stage decreasingly negative, and finally positive.

In the second case depicted on Figure 1 it is assumed that there is little more than enough radioactive material in the level of D to require the ultimate formation of magma. Temperature rises increasingly slowly to about 900°. In a second stage the temperature rise is still slower than in the first stage and, likewise, increasingly slow, since it is permitted only by the slow accumulation of heat in the thick region below D. Thermal gradient s' approaches, but does not attain in its two parts, the rectilinearity expressed by s'' before fusion ensues. When magma begins to form, there will be no further rise of temperature, though Ha may still be a positive quantity. It would be of interest to know whether magma would continue to generate to form a thick reservoir, or whether it would be unstable in these surroundings and would migrate. A discussion of this question is best left, however, to a later stage, when a distribution of radioactive elements more in keeping with that found in the earth will be assumed.

It seems clear that a steady flow of heat from the earth is impossible, even if it is assumed that radioactive material is symmetrically distributed and that all conditions are static except for the slow decay of radioactivity. However, no conditions in the earth are static through long intervals of time. Processes of erosion and migrations of magma are constantly disturbing most factors of the geothermal equation. A consideration of the geothermal factors along with Figure 1 makes it obvious that slight differences in the radioactive content of rocks may decide whether magma will or will never form, or whether magma will form under one region millions of years earlier than under another. Erosion and magma migration disturb not only Hr of the geothermal equation but also Hc in an important way and, therefore, indirectly Ha and the rate of rise of temperature or accumulation of magma.

FACTORS ATTENDING THE GENERATION OF MAGMA

In Figure 1 it is assumed for simplicity that radioactivity is confined to a single level. It is better for other purposes to portray another set of arbitrary conditions which are more in keeping with those of the earth. This is done in Figure 2, where it is assumed that radioactive materials are more or less evenly distributed between the surface and a depth of about 30 kilometers. If thermal gradient 5 seems too low to provide a safe basis for discussion, there can be no such objection to using gradient *10* for this purpose. Gradients

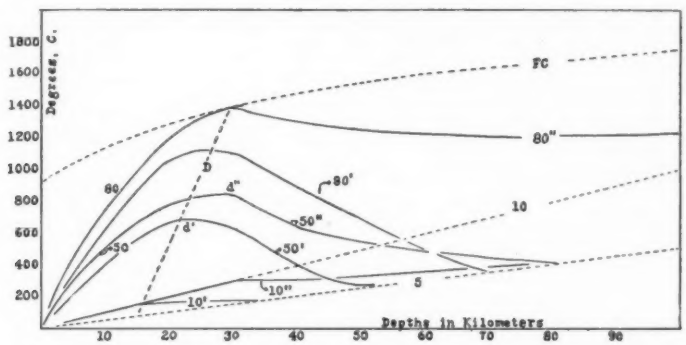

FIG. 2.—A depth-temperature diagram. *FC* represents temperatures of fusion at various depths. Radioactive material is assumed to be more or less evenly distributed between the surface and depths of 30 kilometers. In one case there is assumed to be enough radioactive material to require an ultimate rise of temperature to about 900°, and in another case to the temperature of fusion. Thermal gradients are indicated by numbers which express the corresponding rise in degrees per kilometer of depth near the surface. Gradient *10* typifies the lowest measured thermal gradients.

lower than 10° per kilometer have been measured in the widely separated localities of Mysore in India, Transvaal in Africa, and Ontario and New Jersey in North America. It would not be easy to explain these low gradients in all cases by purely local and shallow causes. The low gradients in Ontario were measured in gold mines[8] which lie in a region of pre-Cambrian rocks where there has been no igneous activity since those remote times. If any portion of the

[8] R. H. Cleland, "Rock Temperatures in the Mines of Northern Ontario," *Can. Min. and Metall. Bull. 256* (1933), pp. 379–407.

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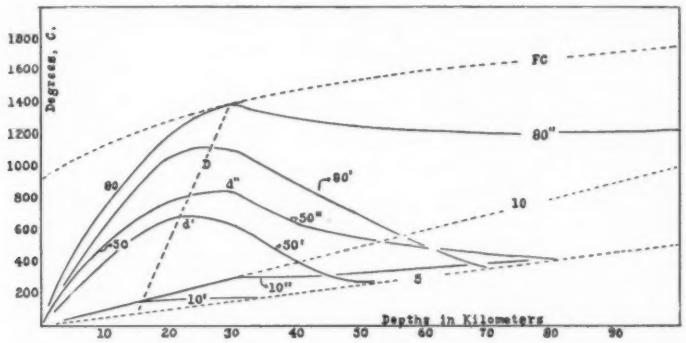

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[8] R. H. Cleland, "Rock Temperatures in the Mines of Northern Ontario," *Can. Min. and Metall. Bull. 256* (1933), pp. 379–407.

outer lithosphere may be considered as having approached a condition of steady heat flow, this region in Ontario might well be chosen to exhibit that condition. For this reason gradient *10* in Figure 2 is better projected as *10″* than as *10′*. The important considerations are that under some regions gradients are much lower than the commonly accepted "average" gradient, and that under other regions the gradients are steep enough to meet *FC* in levels where magma exists or is being generated. It seems safe to infer, therefore, that in the many diverse environments offered by the persistently changing and heterogeneous outer lithosphere, there may exist a fairly complete series of thermal conditions which could be represented in Figure 2 by drawing gradients similar to those already indicated, in all intermediate positions.

In Figure 2 it is assumed in one case that a maximum temperature of about 900° is permitted, an approach to which is indicated by gradient *50″*. With the changes of *50′* to *50″* the depth of the level of maximum temperature increases from *d′* to *d″*, because as time goes on and temperature rises, more heat is lost to the surface and less into the depths. The slope of *D*, the line connecting the maxima on the thermal gradients, is on this account meant to indicate the general tendency of the maxima to descend into deeper levels when temperature increases after long lapses of time.

In the second case illustrated in Figure 2 it is assumed that there is enough radioactive material to insure the eventual formation of magma, as indicated by the junction of thermal gradient *80″* and the fusion-depth curve *FC*. The rate of increase of temperature, always slow even when measured in geologic time units, becomes relatively slower and slower as thermal conditions change from those depicted by *80′* to those of *80″*. Recalling the relations of the factors of the geothermal equation, it is apparent that small fractional differences in the initial quantities of radioactive materials might lead to enormous differences in the time required for the initiation of magma generation, to great differences in the amount of thermal expansion in depths below *D*, and to important differences in the level of *D*. Equally divergent effects on thermal history would result from similarly small variations in the vertical distribution of radioactive material or from slight variations in the thermal conductivity

of rocks in the outer lithosphere, since both of these variations affect the value of *Hc* in the geothermal equation. It is obvious, for example, that a certain amount of radioactive material which at a depth of 19 kilometers would never cause fusion might do so at 20 kilometers.

The thermal effects just indicated might arise in a slightly heterogeneous earth where all except thermal conditions are assumed to be static. But the earth is in no sense static. At all times processes of erosion are leading to the transfer of important quantities of rock material from one region to another, and magmas are migrating in the earth. Each horizontal transfer of material disturbs *Hr* and *Hc* of the geothermal equation. Similarly, a vertical transfer of magma seriously disturbs the radial distribution of radioactive material and, therefore, the values of *Hc* and *He* in the equation. To sum up, it can be said that geologic changes perpetuate a heterogeneity of conditions in the outer lithosphere, which, in turn, perpetuates thermal distortion and igneous activity.

FATE OF MAGMA

When *Hr* of the geothermal equation is an important enough quantity and other factors permit the necessary increase of temperature, magma will form. It follows that no magma would form in the outer earth if there were no radioactivity, and it can only form when radiothermal energy is developed sufficiently to overcome the negative conductivity factor in any particular environment. After liquefaction begins, if *Ha* remains positive, magma will continue to develop. If the magma body thickens downward, part of the accumulating heat is exhausted in raising the temperature, because the temperature of fusion rises with depth. There is an opposite effect if the magma thickens upward; but in this case the approach to the surface brings about an increase in *Hc*, or heat lost to the surface, and consequent decrease of *Ha*, or heat available for magma generation. The upward encroachment of the magma to involve liquefaction at levels within 10 kilometers of the surface would call for very exceptional concentrations of radioactive materials in the region beneath. Such a rise would establish thermal gradients of about 100° per kilometer near the surface, which are extremely high in comparison

with the commonly accepted "average" gradient of about 30° per kilometer. It is of interest in this connection to note that the thickness of the overlying roof cover of the batholith at the time of intrusion is commonly estimated[9] to be less than 5 kilometers, and in several instances less than 1 kilometer. The slow rise of magma into such levels implies the establishment of thermal gradients near the surface which are steeper than 200° per kilometer, and, therefore, incredible concentrations of radioactive materials in regions beneath. Thermal evidence, therefore, is taken as favoring the view that magma has migrated to form the batholith which occupies a secondary chamber above a definite floor, and as being opposed to the concept of a bottomless batholith to form which magma rises more or less passively into shallow levels and makes its own primary chamber by absorbing or stoping the roof.

If magmas were generated under conditions which would permit their slow and uninterrupted accumulation, it might be expected that a continuous shell of magma would eventually be formed. That there has been enough heat available for the formation of a thick shell of magma is obvious enough from the quantitative importance of intrusion throughout geologic time. However, a continuous shell of magma implies a similar shell of weakness, and both thermal and seismic evidences are opposed to the concept of a weak shell.[10] Intrusion seems to have been a more or less continuous process throughout geologic time, so that it is reasonable to conclude that it has been a persistent safety valve for the earth by preventing the formation of a continuous shell of magma which would likely prove to be a treacherous foundation for a "crust." Moreover, it can be shown, for the general case at least, that magma is generated under conditions which cause its migration and ultimate intrusion into shallower levels.

Before the thermal gradient meets the fusion curve, as shown in Figure 2, there is bound to be a considerable rise of temperature in

[9] R. A. Daly, *Igneous Rocks and the Depths of the Earth* (New York: McGraw-Hill Book Co., 1933), p. 126 (with references).

[10] J. S. De Lury, "The Strength of the Earth," *Jour. Geol.*, Vol. XLI (1933), pp. 748–56; "Geologic Deductions from Earthquakes of Deep Focus," *ibid.*, Vol. XLIII (1935), pp. 759–64.

levels below *D*. The longer the time required to attain the fusion temperature, the greater will be the thermal expansion in the underlying region. A rise of the thermal gradient to the attitude of *80″* implies an increase of temperature of several hundred degrees in a region several hundred kilometers thick. Widely different thermal conditions exist under different areas of the earth's surface. One region may be expanding thermally while a neighboring region is undergoing contraction. Again, conditions may decree that under one area there will be relatively little thermal expansion before the initiation of magma formation, while under an adjoining region there may be great expansion before liquefaction begins. The writer has shown elsewhere[11] that differential thermal expansion and contraction lead to changes of elevation at the surface and to the creation of a "head" over some regions in relation to others. There is no virtual "head" until a level of weakness and adjustment is established by the formation of magma. It was indicated also that magma forms initially in a widely disposed sheet and that expansion resulting from change of state causes the sheet to spread horizontally in its own plane. When the sheet is sufficiently large, the "head" leads to subsidence, the energy of which is available for the forcing of magma into surrounding regions under less "head" and for the generation of additional magma from frictional heat. It seems probable that the most important and direct source of heat for the breeding of magma is mechanical heat from subsidence.[12]

The statement that there is no virtual "head" until magma is formed may need an explanation. The reader is warned that the writer does not accept the assumptions of isostasy. The isostasist would not grant the existence of a "head," notwithstanding the abundant evidence that the earth has suffered profound distortions and changes of elevation. Isostasy suggests no explanation of hypogene activities, and an acceptance of its assumptions places limitations which seem to prevent an explanation. That the generation of magma may lead to the establishment of a "head" in a thermally distorted earth can be made clear by a simplified example. Let it be

[11] De Lury, "The Magmatic Wedge," *loc. cit.*

[12] J. S. De Lury, "Magmas from Subsidence," *Amer. Jour. Sci.*, Vol. XXIII (1932), pp. 357–68.

assumed that two earth columns meet the surface in the same horizontal plane. One column is thermally expanded to a depth of 500 kilometers, and the adjacent vertical column is not expanded or may suffer thermal contraction to the same depth, so that at the surface the tops of the two columns are no longer in the same plane and one surface may stand 2 kilometers above the other. Next, it is assumed that magma is generated as a sheet in the thermally expanded column at a depth of 20 kilometers and is injected horizontally into the adjacent column. The latter column will then have a sheet of magma in a level 18 kilometers from the surface. It follows that above the level of magma formation the weights of the two columns are approximately as 20 to 18, one to the other. Magma is a persistent component of the outer lithosphere throughout geologic time, and even the isostasist must admit that probably every important migration of magma is accompanied by some restoration of balance in the outer lithosphere. Magma is the only known highly mobile material in the earth, and mobility permits adjustments.

SUMMARY AND APPLICATION OF VIEWS

With the aid of a simple thermal equation which involves the various thermal factors of importance in outer shells, it is shown that small differences from uniformity in vertical and horizontal distribution of radioactive elements, and similarly small differences in the thermal conductivities of rocks, may lead to vast differences in the time required for magma generation, to important differences in the thermal expansions of thick columns of the earth, and may decide whether magma will or will not form and, to some extent, the level of its generation. It is shown, moreover, that magma probably migrates on an important scale through great horizontal distances. Processes of erosion and migrations of magma are on a scale which, in view of the small demands made on heterogeneity of conditions to produce differential thermal effects of importance, is grand enough to keep the earth continually in the throes of distortion.

The writer can think of no greater forces than those to which he has appealed in an attempt to explain the causes of hypogene activities. The greatest force is involved with thermal distortion. Next is the mighty force which arises from the change of volume caused by

the fusion of rock to form magma. Last is the force from the energy of subsidence of regional and thick masses of the outer lithosphere, which is the one mainly appealed to in explanation of forceful intrusion and its concomitant deformation of the outer shell. Magma is generated usually in environments which require its expulsion, probably in most cases before it can assume great thickness.

Magma is likely generated in most cases within an outer shell only a few tens of kilometers thick, and in an environment, thermal and otherwise, which favors the extension of the magma horizontally rather than vertically. There is compelling thermal evidence against the view that a body of magma can thicken and rise passively to form a batholith which is without "bottom," which occupies a primary magma chamber, and which has finally crystallized with its apex within 10 kilometers of the earth's surface. The slow and upward invasion of the surface by such a batholithic magma to a level only 5 kilometers from the surface would imply that thermal gradients of about 200° per kilometer would be established. Gradients as steep as these would require the presence of unbelievable concentrations of radioactive elements in the region beneath. Even if such concentrations were admitted, there arises the serious difficulty of accounting for the fact that many regions which were invaded by ancient batholiths now have thermal gradients as low as 10° and 20° per kilometer. The writer concludes, therefore, that batholithic magmas must migrate in large measure from distant localities and must tap sources of heat which are altogether too vast to be supplied by the region immediately beneath the batholith. This view permits an understanding of the history of mobile belts which linger through long geologic intervals in restricted localities and are all the while areas of excessive thermal losses.

If the writer's views on the genesis and migration of magma are well founded, there are good reasons for questioning the common interpretation that the explanation of the diversity of igneous rocks lies largely in processes of differentiation. There is good evidence that processes of both differentiation and assimilation contribute to variation in composition. Advocates of differentiation were so impelled by their evidence that they assumed mechanisms of intrusion which best fitted the requirements of that process. It may well be

that their assumptions are poorly founded and that assimilation has been the guiding process in producing diversity of composition. The writer is speaking here of the variation found in batholiths and in lavas, and not of that which is shown by sial and sima in a world-wide way. Unquestionably, some processes of differentiation have operated in the earth and are still operating; but it should be kept in mind that igneous processes have so far failed to produce sial in long-established volcanic centers of the deeper oceanic basins, while diversity of lavas and conspicuous sial are fairly characteristic of continental volcanoes. It is still an open question whether a "mixing" or an "unmixing" process has been the dominant one in geologic time, and, therefore, whether sial was largely inherited or has been differentiated in geologic time.

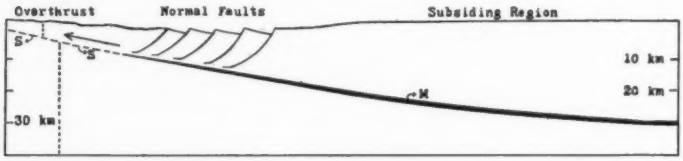

FIG. 3.—A vertical section of the outer lithosphere with a fivefold or tenfold exaggeration of the vertical scale. Subsidence drives a sheet of magma, *M*, to the left, causing the development of a dry "sole," *S*, and an overthrust. Normal faulting follows above the outermost part of the "sole" occupied by magma. The sum of compressional effects, indicated by the displacement of the vertical, broken line, equals the sum of tensional effects in the horizontal displacements of the normal faults.

Predictable effects of the writer's suggested mechanism of intrusion are illustrated in Figure 3. A sheet of magma, *M*, generated in part and driven by the subsidence of a broad section of the lithosphere, 30 kilometers thick, migrates to the left. The causes suggested for the slope of *D* in Figure 2, together with the fact that strength decreases upward in rocks which are not too close to the fusion temperature, determine that the magma will occupy higher levels as migration proceeds. The expansion of the sheet of magma finds release in the formation of fracture, *S*; and the differential "drag" exerted by the sheet on the overlying lithosphere leads to overthrusting above the dry part of the "sole" and to normal faulting above the magma.

In certain instances, as in the case where there is an obstruction ahead, the overthrust flake may fold to give the type of folding shown by the Jura Mountains. In a later stage magma may migrate beneath such folds and may slowly accumulate to form a batholith. Figure 4 illustrates the general form of a batholith which might be formed in the manner just described. In the same figure is pictured a stippled region which serves to illustrate the "bottomless" batholith, in contrast with the favored form indicated in solid black.

It is possible that an accumulated sheet of mobile magma might break out by expansion to the surface without involving enough frictional drag to cause important tensional and compressional de-

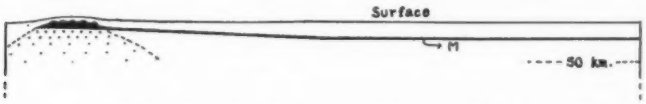

FIG. 4.—A vertical section of a wide portion of the outer lithosphere. Magma, *M*, flows as a sheet from beneath a subsiding region and to the left. It accumulates beneath a folded geosyncline and slowly builds a batholith, indicated in solid black. The stippled region crowned by solid black shows in contrast the kind of batholith which is assumed by some authorities to rise passively and to be "bottomless."

formations in the outer lithosphere. Great fissure eruptions and floods of basaltic magmas may be so formed and expelled. The same explanation might be suggested for the great volcanic ridges and chains of the deep Pacific basin.

The attention which has been given to the origin of major bodies of igneous rock does not imply that all igneous masses have the same mode of emplacement. The outer lithosphere is too heterogeneous to permit any such implication. It is the writer's view, however, that intrusion is usually forceful and that, even in those instances where there is a suggestion of a "passive" rise of magma, such a description must be used in a relative sense. It is probable, for instance, that a forceful and major migration of magma will lead to deformations of the outer lithosphere, which lead, in turn, to minor and local intrusions with "passive" attributes.

ORIGIN OF THE SALTON VOLCANIC DOMES, SALTON SEA, CALIFORNIA

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ABSTRACT

The location of the Salton volcanic domes and the alinement of the associated mud volcanoes strongly suggests their affiliation with the buried extension of the San Andreas fault. Two surface trends are evident—the northeastward locus of the volcanoes, and the northwestward line of mud geysers. The latter coincides almost exactly with a southeastward extension of the San Andreas fault from 15 miles to the northwest. A detailed magnetic survey indicates that the subsurface material is not confined to the immediate vicinity of the domes. Steep magnetic gradients observed over the flats some distance from the line of volcanic hills are interpreted as the magnetic effect of the sloping surface of the underground igneous mass. In consequence of wind-directed wave attack during the presence of Lake Cahuilla and Salton Sea the lighter pumiceous materials have been concentrated to the lee of the hills in wave-built terraces or "tails," which at the southernmost volcano have accumulated in sufficient quantities to be of commercial importance. At this same volcano a peripheral distribution of obsidian with relation to pumice leads to a unique interpretation of its structure and origin. Fumarolic carbon dioxide gas trapped in the valley sediments to the northeast of the domes has been recently exploited for the manufacture of "dry ice."

The Salton volcanic domes lie very near the bottom of the inland depression which structurally constitutes the northern extension of the Gulf of California. This sub–sea-level portion of the Gulf trough includes in a broad way three better-known geographic units, namely, Coachella Valley, Salton Sea, and Imperial Valley. Salton Sea, occupying the center of the basin, separates Coachella Valley on the north from Imperial Valley on the south. However, the separation is not purely geographical inasmuch as the Coachella Valley is a comparatively narrow structural basin whereas the Imperial Valley is considerably broader and probably includes several parallel depressed and waste-covered fault blocks. The principal structural feature of this region is the San Andreas fault, which practically coincides with the east side of the Coachella Valley. Southeastward it probably passes beneath the Salton Sea and under the Imperial Valley.

THE VOLCANIC DOMES

There are 5 volcanic domes lying roughly parallel to the southeastern shore of the Salton Sea. The length of the line of volcanoes

FIG. 1.—Salton volcanic domes showing the locus of the mud pots and the wave-built pumice deposits on the east side of the hills

is about 4 miles. As late as 1914 the hills stood as islands in the Salton Sea (Fig. 2), but by the spring of 1935 the shoreline of the sea had receded about $1\frac{1}{2}$ miles from the volcanic cones. None of the hills rises more than 100 feet above the level valley floor which at this point is 240 feet below sea-level.

Rogers[1] has briefly described the rocks of these hills as "rhyolitic obsidians and pumices and their alteration products." He was especially interested in Mullet Island, where he found that the original rhyolitic material had been altered to a metamorphic rock composed

FIG. 2.—Looking southwest from Pumice Buttes Island. Salton Dome and Obsidian Buttes in distance partly inundated by Salton Sea. Photograph by MacDougal, 1912.

essentially of tridymite and feldspar. Here, as in the case of many viscous rhyolitic extrusions, the flow structures are arched into a gentle dome. But, although the structure as exposed is quaquaversal, the igneous mass as a whole is probably mushroom shaped, as a well drilled on the flank of the dome reached sedimentary material in a few tens of feet.

Mullet Island has attracted much attention locally because of the nearby hot springs and mud "pots" which discharge considerable quantities of steam, carbon dioxide, some hydrogen sulphide, and water laden with sodium chloride. Much iron oxide forms in some of

[1] A. F. Rogers, "Salton Volcanic Domes of Imperial County, California," *Geol. Soc. Amer. Proceedings for 1934*, p. 328.

the muds, perhaps as the result of the extreme oxidizing action of the gases on the sediments.

Pumice Buttes, about 2 miles south of Mullet Island, are two small coalesced volcanic cones or domes as shown in Figure 1. The structure of the north hill is markedly quaquaversal and like Mullet Island the igneous mass is probably mushroom shaped with the outer margin of the body partly covered by valley fill. The south hill is almost entirely covered with mud flows and terrace deposits. Erosion by wind and waves has partially exhumed the once more ex-

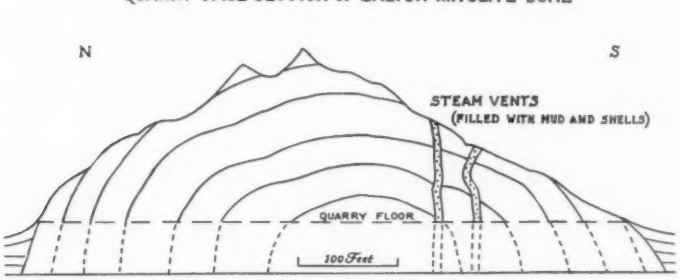

FIG. 3.—Quarry face section of Salton Dome

tensive mud flows on the west side, producing steep cliffs in which the texture and crude bedding of the consolidated mud flows are well exposed.

Salton Dome is interesting chiefly because of the excellent exposure of its internal structure in a quarry on its west side. The flow structures of the dome are nearly vertical on the flanking limbs and in this respect the mass has a plug-like form in contrast to the mushroom forms of the previously described volcanic cones. Numerous small open vents from which continued slow exhalations of steam escape are present among the craggy outcrops. In the quarry face are exposed two of these vents filled with mud and small shells deposited during the existence of Lake Cahuilla.

The name Obsidian Buttes given to the southernmost of the volcanic hills is not apt in that most of the rock is pumice. The name presumably arose from the several small buttes of obsidian which

are distributed around the periphery of the nearly circular pumice field (Fig. 1). The volcanic cone is composed of a central dome-like hill surrounded by a lower field of pumice with buttes of obsidian at the outer margin.

The magma which rose to form Obsidian Buttes was exceedingly rich in gases. During the rise of the lava to the surface, and before it had congealed, most of the gas-rich material had separated and risen to the top of the lava column. Once at the surface the gas-rich upper part rapidly expanded and cooled to form the highly cellular and light pumice. Below it was molten gas-lean material which was

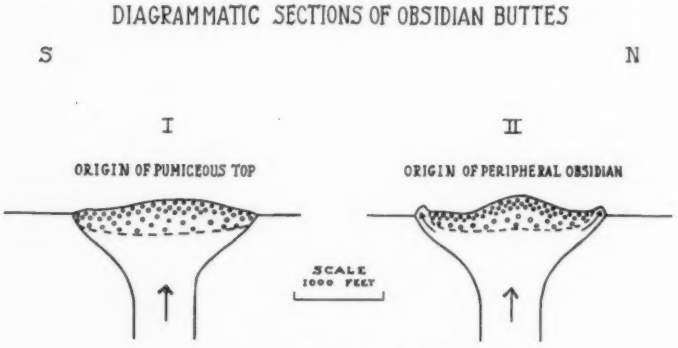

FIG. 4.—Diagrammatic section of Obsidian Buttes

effectively capped temporarily by the brittle but light pumiceous material. However the magmatic pressures were not entirely relieved at this stage and additional surges from below found much easier avenues of escape by flowing laterally to the edge of the pumice cap where the molten material rose nearly vertically to the surface and congealed to form the small obsidian buttes. Several of the buttes rise very abruptly above the outer flat valley floor and the inner pumice area (Fig. 5). The flow lines are usually tangential to the pumice field, but may be very much contorted. Such an occurrence is unique, so far as the authors are aware, and probably would form only under specialized conditions obtained with a rather complete segregation between the gas-rich and gas-lean phases of a rhyolitic lava.

SIGNIFICANCE OF THE VOLCANIC CONES

The Salton volcanic domes are undoubtedly of Quaternary age, very young, for the fading stages of volcanism are still evidenced by the mud pots and steam geysers. It is probable that molten rock lies not over a few thousand feet below the valley floor. One is immedi-

FIG. 5.—Obsidian outcrop covered with calcareous tufa, near the top of one of the peripheral extrusions at Obsidian Buttes.

ately struck by the isolation of the volcanic cones on the apparently undisturbed level floor of the basin and by their linear distribution, which suggests some underlying structural control. This alinement prompted a magnetic investigation on the expectation of finding a buried fault or underground igneous mass. The completed magnetic survey indicates the latter, but its emplacement may have been determined by an earlier fracture.

The position of the volcanic cones is roughly on the extended strike of the San Andreas fault, but their alinement makes a large angle with the regional trend of the fault. Nevertheless, their position directly in line with the San Andreas rift appears to be more than fortuitous.

Even more convincing evidence for a buried fracture was obtained by mapping the positions of the mud pots in the vicinity of Mullet Island. It was found that there are four groups of mud geysers in a straight line striking N. 45 W. (Fig. 1). This is also the regional trend of the San Andreas fault 20 miles to the northwest, and furthermore, their loci are exactly in line with this major fracture. It is also interesting to note in this connection that on the west side of Volcano Lake in Lower California a more prominent and active group of mud geysers occurs directly in line with the more active San Jacinto fault. A magnetic profile also indicates its buried expression along this line. Thus the alinement of the mud geysers near Mullet Island for almost 3 miles is as good evidence as has been found for the southeastward extension of the buried San Andreas rift.

THE CARBON-DIOXIDE GAS FIELD

Carbon dioxide has been known to issue from the boiling springs and geysers around Mullet Island for many years. About seven years ago a well was drilled in the altered rhyolite on the flank of the hill. It blew considerable gas and subsequently more than a dozen wells have been drilled in the vicinity in quest of carbon dioxide. One was drilled on the flank of Salton Dome and after penetrating sediments for over a thousand feet parallel to the neck encountered live steam. Finally, after drilling again into live steam and high pressure underlying the north hill at Pumice Buttes, attempts to obtain carbon dioxide directly over the volcanic cones were abandoned. The later wells have been drilled on the flats east of the cones.

All of the producing wells are located in a small area about 2 miles directly east of Mullet Island and north of the line of mud geysers. The principal producing horizon appears to be between depths of 400 and 500 feet. The initial pressures, usually between 200 and 300 pounds per square inch, decrease after some production.

The general opinion among the operators in the district is that

the carbon-dioxide gas has resulted from the action of superheated steam and other gases on the sedimentary carbonate rocks. They note that "lime" rocks are present near the producing horizons. On the other hand, the emanation of carbon dioxide from volcanoes is well known. The Salton volcanoes themselves give off carbon dioxide and other gases, and it appears more probable that the producing horizons are sedimentary structural traps into which the juvenile magmatic carbon dioxide has migrated.

THE WAVE-BUILT PUMICE DEPOSITS

The pumice deposits are wave-built terraces, but their position in relation to the wave cutting is not the usual one. A complete understanding of the wave-built pumice deposits necessitates a review of the recent physiographic history of the basin.

Prior to the last outbreak of the Colorado River and the flooding of the basin during the period 1904–7, the area now occupied by the Salton Sea was a dry playa with local saline accumulations. The basin had been dry continuously since the coming of the white man. However, older and higher shorelines furnish evidence of an earlier water body, and Indians of the region tell of this lake and its gradual disappearance.

The name Salton Sea applies only to the twentieth-century inundation of the basin. The earlier water body has been referred to as Lake Cahuilla. Buwalda and Stanton[2] have pointed out that the pre-Salton Sea lakes of Quaternary time were fresh water, and that the prominent high-water shoreline was formed by Lake Cahuilla and not by an extension of the Gulf of California. Moreover, the sub–sea-level depression of the Salton basin took place after or concurrently with the establishment of the Colorado River cone as an effective dike against the Gulf of California.

It is possible that the sinking of the basin may have initiated the volcanic activity. That the volcanoes are not older than Quaternary is evidenced by their very young aspect and their very slight dissection. Prior to the building of the Colorado River cone most of the region was above sea-level and was undergoing erosion with drainage

[2] John P. Buwalda and W. Layton Stonton, "Geological Events in the History of the Indio Hills and the Salton Basin," *Science*, Vol. LXXI, p. 105.

to the gulf. That the volcanoes were formed after the early stages of Lake Cahuilla is shown by the fact that only the very outer margins of their surface forms are covered by lake deposits. That the volcanoes were present during at least the later stages of Lake Cahuilla is indicated by the shorelines above those formed by the Salton Sea. That a considerable time elapsed between the last desiccation of Lake Cahuilla and the appearance of Salton Sea is shown by the pronounced dissection of the Cahuilla wave-cut cliffs and pumice terraces.

FIG. 6.—Details of the wave-built terraces at Pumice Buttes

Thus, the Salton volcanic cones were formed some time after the building of the Colorado delta dike and during the Lake Cahuilla stages. When the Colorado River flowed into Lake Cahuilla and kept it filled to its maximum, some 30 feet above sea-level, the tops of the cones were covered by more than 150 feet of water. At other times when the river was diverted directly to the gulf, Lake Cahuilla continuously shrank, and if the diversion continued 50 years or more the lake practically disappeared. The lake-level rarely remained stationary except when overflowing to the gulf, at which times the action of the waves was above the cones. Since at other times the level of the lake was either rising or sinking, the periods of effective wave action on the volcanoes were comparatively short.

Nevertheless, at times they were subjected to wave attack, the

effectiveness of which varied with the type of rock. Mullet Island, composed of altered but resistant rhyolitic material, and Salton Dome composed of relatively dense rhyolite, were beveled only slightly. Pumice Buttes, with their partially consolidated mud flows and Obsidian Buttes, composed of light frothy pumiceous material, were easy prey to the wind-directed wave attack. The prevailing winds in this part of the valley are from the west. The soft and light pumiceous materials eroded from the western (windward) side of the

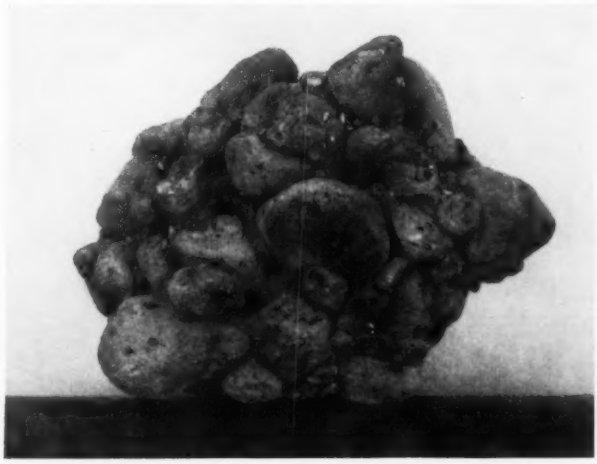

FIG. 7.—A fossiliferous pumice conglomerate from the wave-built terrace at Obsidian Buttes. Numerous small fresh-water gastropods occur in the calcareous tufa cement. $\times\frac{3}{4}$.

islands were sorted, buffeted, and carried to the eastern (lee) side of the islands. This resulted in a natural selection and concentration of high-grade pumice in the terraces or "tails" which formed to the lee of the islands. The combination of wave-cutting on one side and terrace-building on the other side has given some of the hills a noticeable asymmetrical profile.

At Pumice Buttes this selection was largely from the tuffaceous material of the mud flows which does not contain so much high-quality pumice as Obsidian Buttes. At the latter volcanic cone the top of the flow contained the "cream" of the pumice. It was exceed-

ingly cellular and light, and the buoyant material was spread far and wide over the valley. The ancient beach line many miles to the east contains much of this material. However, large quantities of excellent pumice were waterlogged or otherwise deposited in the "tail" at Obsidian Buttes. Here the deposit is mined and water-sorted for the highly cellular glass which is used in the manufacture of certain acoustic plasters and polishing blocks. The larger fragments often contain cavities 2 or 3 inches in diameter spun across with fine tubular threads. The present erosion surface shows none of the very high-grade pumice found in the sedimentary deposit, indicating that the original surface of the extrusion was much more frothy than the material uncovered by erosion.

THE MAGNETOMETRIC RESULTS

That the volcanic domes occur along a slightly curved line suggests a possible common fissure along which the extrusive material reached the surface at the various points. With this in mind, several magnetic profiles were made across the curve joining the buttes, but no striking anomalies were observed. Next, a detailed vertical intensity map of the entire area was made in an effort to determine the extent of the subsurface igneous material. This was done by placing observation stations over the area about every half-mile, but where the magnetic gradients were found to be steep the stations were placed much closer together in order to obtain a more accurate representation of the magnetic features associated with the buttes.

In the immediate vicinity of the volcanic cones the stations were only a few hundred feet apart because it is in these areas that the magnetic intensity has the greatest lateral variation. In all, observations were made at about 200 stations during the survey. The presence of swamps in the vicinity of the Alamo River prevented a magnetic survey of this part of the area.

The method used during the investigation is very similar to the conventional system of making a barometer survey for elevation. A Schmidt type of vertical intensity variometer was used as a combined field and stationary recording instrument. Stationary observations are necessary to obtain the background reading so the field observations may be corrected for diurnal and other variations which may affect the magnetic component being studied. Instead of mak-

ing a stationary continuous reading of the component, the variometer was read at a conveniently located station at brief intervals of time during the field survey. In this manner a continuous approximation of the variations was obtained by interpolation methods. This procedure gave the necessary data for the correction of the routine field observations for diurnal effects. Temperature correc-

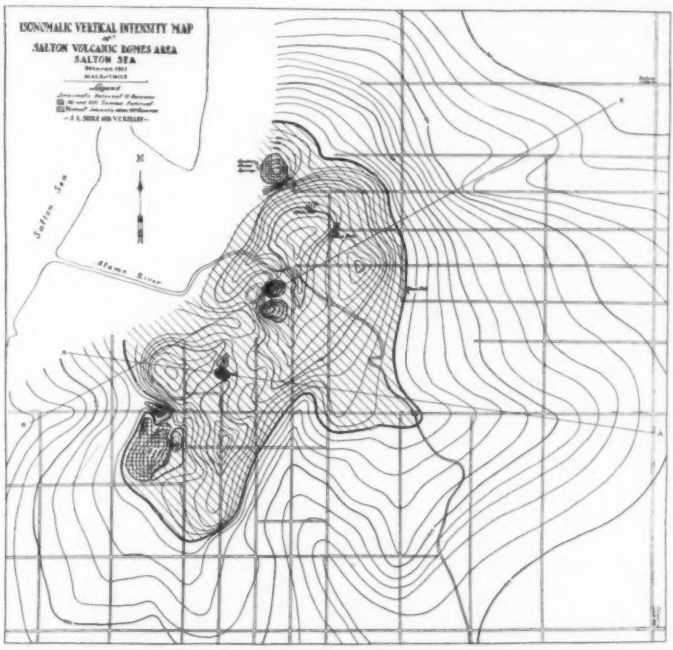

FIG. 8.—Isonomalic vertical intensity map of Salton volcanic domes area

tions and adjustments were made for the normal variations of the vertical intensity component and for changes in latitude and longitude. The resulting values were reduced in such manner that if any variation was noted it could be attributed to geological conditions associated with areal changes of magnetic susceptibility. These values were then plotted on a map and isonomalic lines were drawn (Fig. 8).

The detailed magnetic survey indicates that the underground ig-

neous mass is not confined to a fissure passing through the hills, nor does it indicate that the mass is confined to the immediate vicinity of the hills. The vertical intensity anomalies indicate that the igneous mass at a considerable depth underlies the whole area occupied by the volcanic cones and other active features such as the mud geysers.

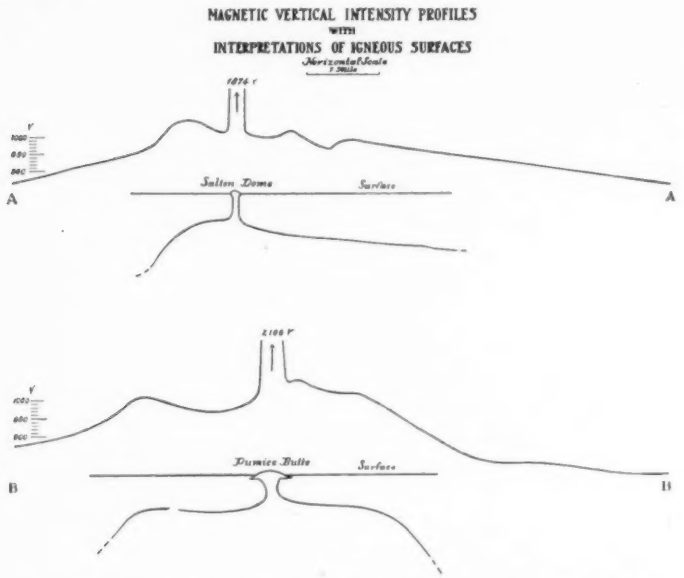

FIG. 9.—Magnetic vertical intensity profiles with interpretations of the subsurface igneous bodies along lines *A–A* and *B–B* of Fig. 8.

Steep magnetic gradients observed over the flats some distance from the curved line of hills indicate that a rapid lateral change occurs in the magnetic susceptibility of the subsurface materials. This conspicuous change in the magnetic gradient may be interpreted as the magnetic periphery of a large, deep, igneous mass which reaches the surface at various points along a fissure or fault in the uppermost layers.

Sections *A–A* and *B–B* of Figure 9 show graphically the changes of intensity along certain directions. The eastern portion of *A–A*

indicates that the igneous mass may extend eastward, forming a nose-shaped body. The northeast portion of *B–B* may be interpreted as representing a steep slope of the periphery of the igneous mass.

In conclusion it may be stated that the survey demonstrates that a very marked differential permeability exists between the sediments and the igneous rocks of the area. It is this fact which makes the method useful in detecting the underground extent of the igneous body although buried beneath sedimentary materials. A very much more detailed magnetic survey may show even more minute details, but the general magnetic expression of the area will not be changed.

ACKNOWLEDGMENTS.—The authors wish to express appreciation to Professors J. P. Buwalda and G. H. Anderson for suggestions in preparation of the paper. Also to Professor A. R. Whitman goes recognition for an earlier introduction to some of the problems of the area.

LOCAL DENSITIES AFFECT VALUES OF GRAVITY

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ABSTRACT

Virginia and Maryland, with parts of adjoining states, are included in the present gravimetric study, which shows that the isostatic anomalies are closely related to densities of underlying geological formations in this area. No definite relationship of the anomalies to the topography of the area is found.

The fifty-eight gravity stations in Maryland, Virginia, West Virginia, eastern Ohio, southern Pennsylvania, Delaware, southern New Jersey, and the District of Columbia, which are shown on the sketch map (Fig. 1), are very interesting from the standpoint of geology and geophysics. The isostatic anomalies for these stations, based on the international gravity formula and a depth of compensation of 96 kilometers, are shown on the map (Fig. 1).

For many years it has been realized that geological structure has a bearing on the value and sign of gravity anomalies at nearby stations. Where there is an outcrop of heavy rock, such as that of the pre-Cambrian age, the gravity anomaly at a station close by is positive in nearly all cases, or if negative, it is quite small. As a matter of fact, the largest positive anomalies for gravity stations in the United States are at stations that are on or close to outcropping pre-Cambrian rock.

There are a number of stations in the area under discussion which are on or near outcrops of pre-Cambrian rock. At Philadelphia, Station No. 24, the gravity anomaly is +22 milligals, and there is an outcrop of pre-Cambrian just to the west of that station. At Laurel, Md., Station No. 209, the anomaly is +33, and there is an outcrop of pre-Cambrian nearby. In the District of Columbia are six gravity stations, Nos. 21, 22, 84, 321, 337, and 338, with anomalies ranging from +33 to +38. Pre-Cambrian rocks outcrop in the District and no doubt lie only a short distance below the surface in other places.

At Rockville, Station No. 212, the anomaly is +45, and at Gaithersburg, Station No. 322, it is +38. Near each of these places is pre-

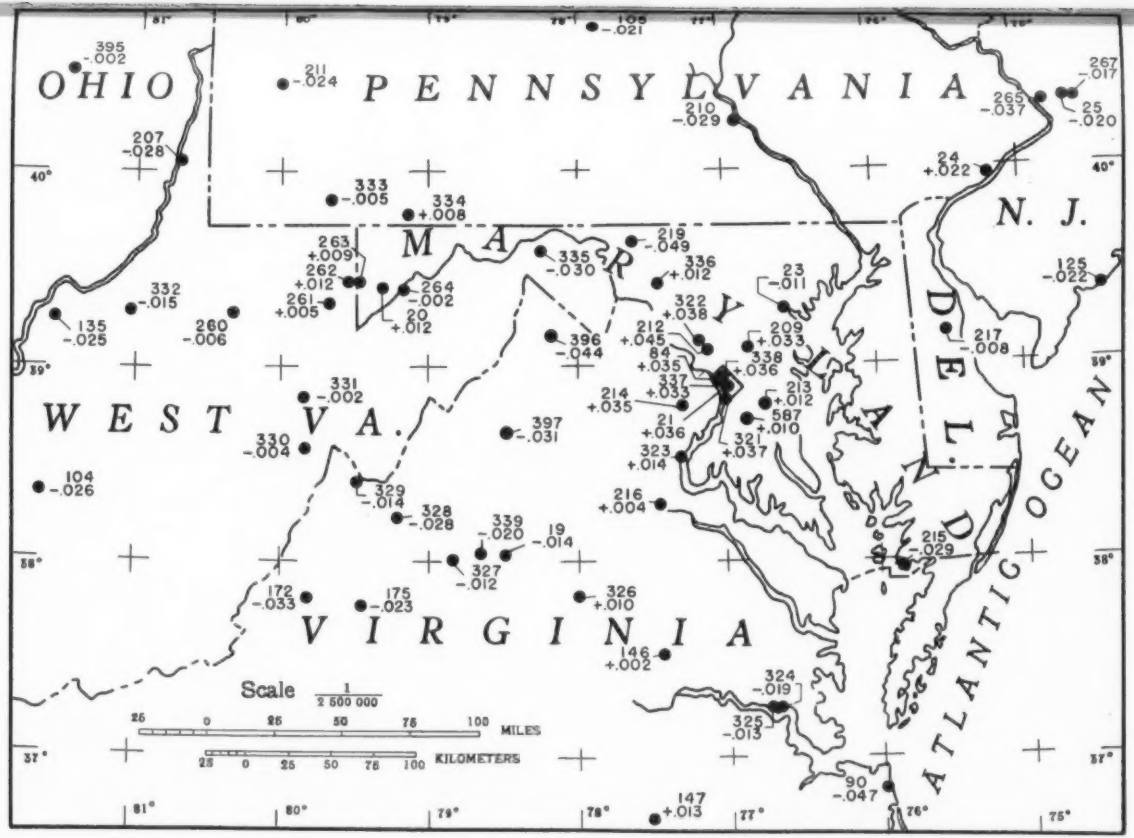

FIG. 1.—Gravity stations in Maryland, Virginia, West Virginia, eastern Ohio, southern Pennsylvania, Delaware, southern New Jersey, and the District of Columbia.

Cambrian outcrop. Again, there are outcrops of pre-Cambrian near Quantico, Va., Station No. 323, where the anomaly is +14 and near Fredericksburg, Va., Station No. 216, where the anomaly is +4.

Much has been written about the relation of gravity anomalies to the elevation of a region. The part of West Virginia which is shown on the sketch has an average elevation greater than that of any other part of the area under consideration having equal size. The average anomaly for the West Virginia stations is −10. I think it can be generally stated that where there are many gravity stations in a mountain area, with the stations fairly closely spaced, the average anomaly will not be far from zero. This is true whether the area is in North America, Europe, or some other continent. This, it seems to me, is a clear indication that the crust under mountain areas is in equilibrium, or nearly so. As a matter of fact, a mountain area furnishes the very best test of isostasy because of the large amount of topography involved.

In contrast to the pre-Cambrian anomalies mentioned above, which are all positive, the sketch shows a line of stations, Nos. 396, 219, 397, 328, and 172, for which the isostatic anomalies range between −28 and −49. An inspection of the sketch indicates that the area having the large negative anomalies is comparatively narrow. It seems to me quite evident that this area must be underlain by rather thick beds of density less than normal.

The station at Virginia Beach, No. 90, has an anomaly of −47. It is certain that the Virginia Beach area is underlain by thick beds of sediments having a density less than normal. In this connection it is interesting to note that recent seismic work has been done over the continental shelf off the Virginia coast by Dr. Maurice Ewing of Lehigh University, with the co-operation of the Coast and Geodetic Survey. Since Ewing's results are not yet available, I can make no statement as to what he found. If seismic work were done off the coast directly opposite Virginia Beach, I think it is reasonably certain that rather thick beds of recent sediments would be disclosed.

It is hoped that additional gravity stations may be established in northern and western Virginia within the next few months to outline as well as is practicable the strip just described, which has the large negative anomalies.

TABLE I

ISOSTATIC ANOMALIES

(Based on international formula and a depth of compensation of 96 km.)

Station No.	Name	Latitude	Longitude	Elevation (Meters)	Bowie Anomaly (Gal)
19	Charlottesville, Va.	38°02.0′	78°30.3′	166	−0.014
20	Deer Park, Md.	39 25.0	79 19.8	770	+ .012
21	Washington, D.C. (C&G.S.)	38 53.2	77 00.5	14	+ .036
22	Washington, D.C. (Smithsonian)	38 53.3	77 01.5	10	+ .038
23	Baltimore, Md.	39 17.8	76 37.3	30	− .011
24	Philadelphia, Pa.	39 57.1	75 11.7	16	+ .022
25	Princeton, N.J.	40 21.0	74 39.5	64	− .020
84	Washington, D.C. (Bur. of Stand.)	38 56.3	77 04.0	103	+ .035
90	Virginia Beach, Va.	36 50.5	75 58.4	4	− .047
104	Charleston, W.Va.	38 20.9	81 37.7	184	− .026
105	State College, Pa.	40 47.9	77 51.8	358	− .021
125	Atlantic City, N.J.	39 21.9	74 25.0	3	− .022
135	Parkersburg, W.Va.	39 16.0	81 33.7	185	− .025
146	Richmond, Va.	37 32.2	77 26.1	30	+ .002
147	Emporia, Va.	36 40.2	77 31	37	+ .013
172	Clifton Forge, Va.	37 49.1	79 49.6	325	− .033
175	Lexington, Va.	37 47.2	79 26.6	324	− .023
207	Wheeling, W.Va.	40 04.0	80 43.4	205	− .028
209	Laurel, Md.	39 06.3	76 51.0	54	+ .033
210	Harrisburg, Pa.	40 16.0	76 53.1	104	− .029
211	Pittsburgh, Pa.	40 27.4	80 00.6	235	− .024
212	Rockville, Md.	39 04.9	77 08.8	129	+ .045
213	Upper Marlboro, Md.	38 49.0	76 45.2	12	+ .012
214	Fairfax, Va.	38 47.7	77 19.6	115	+ .035
215	Crisfield, Md.	37 58.8	75 50.7	1	− .029
216	Fredericksburg, Va.	38 18.1	77 27.5	16	+ .004
217	Dover, Del.	39 09.7	75 32.0	12	− .008
219	Hagerstown, Md.	39 38.5	77 43.5	166	− .049
260	Clarksburg, W.Va.	39 16.8	80 20.3	306	− .006
261	Rowlesburg, W.Va.	39 20.8	79 40.2	421	+ .005
262	Terra Alta, W.Va.	39 26.9	79 32.9	790	+ .012
263	Corinth, W.Va.	39 25.6	79 29.4	751	+ .009
264	Kitzmiller, Md.	39 23.6	79 10.4	493	− .002
265	Pennington, N.J.	40 20.0	74 47.6	56	− .037
267	Plainsboro, N.J.	40 20.0	74 35.8	26	− .017
321	Washington, D.C. (Naval Research Laboratory)	38 49.4	77 01.5	7	+ .037
322	Gaithersburg, Md.	39 08.2	77 11.9	155	+ .038
323	Quantico, Va.	38 31.5	77 17.2	12	+ .014
324	Williamsburg, Va.	37 15.6	76 40.8	26	− .019
325	Williamsburg, Va. (Col. of William and Mary)	37 16.3	76 42.6	30	− .013
326	Hadensville, Va.	37 49.5	78 00.2	135	+ .010
327	Afton, Va.	38 01.8	78 51.5	588	− .012
328	Churchville, Va.	38 13.9	79 11.0	486	− .028
329	Monterey, Va.	38 23.5	79 33.0	1065	− .014
330	Durbin, W.Va.	38 36.0	79 50.9	1149	− .004
331	Beverly, W.Va.	38 53.1	79 50.7	638	− .002

TABLE I—*Continued*

Station No.	Name	Latitude	Longitude	Elevation (Meters)	Bowie Anomaly (Gal)
332	Pennsboro, W.Va.	39°16.4′	81°03.2′	307	− .015
333	Uniontown, Pa.	39 51.3	79 39.6	789	− .005
334	Summit Mills, Pa.	39 47.6	79 10.0	967	+ .008
335	Berkeley Springs, W.Va.	39 37.0	78 15.6	280	− .030
336	Braddock Heights, Md.	39 25.7	77 30.0	291	+ .012
337	Washington, D.C. (Com. Bldg.)	38 53.6	77 02.0	0	+ .033
338	Washington, D.C. (Geoph. Lab.)	38 56.6	77 03.4	88	+ .036
339	Mechum River, Va.	38 03.8	78 39.0	151	− .020
395	Dover, Ohio	40 31.9	81 28.4	276	− .002
396	Winchester, Va.	39 09.9	78 09.6	196	− .044
397	Luray, Va.	38 40.1	78 28.8	286	− .031
587	Cheltenham, Md.	38 44.0	76 50.6	66	+ .010
	Mean with regard to sign				− .003
	Mean without regard to sign				.021

The purpose of this paper is to set forth the data for the gravity stations in the area around the District in order that geologists and geodesists who are thoroughly conversant with the geology of the region may be able to investigate the relation of the gravity anomalies to the geological structure. If a definite relation between anomalies and known structure is found, it may be possible to interpret gravity anomalies in terms of structure for regions where the structure is unknown.

Table I gives the names of the stations, their latitudes, longitudes, and elevations, and the isostatic anomalies based upon the international gravity formula, together with the new value for the base station at Washington, D.C., which was derived from observations made there and at the international base station at Potsdam, Germany, in 1933 by the late E. J. Brown, an engineer of the Coast and Geodetic Survey. Descriptions of the stations in sufficient detail to enable one to visit the exact point where the observations were made may be obtained from the director of the Coast and Geodetic Survey, Washington, D.C.

MONTLAKE—AN AMAZING SINKHOLE

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ABSTRACT

Montlake is a large, spectacular sinkhole, walled with massive sandstone, located on the Cumberland Plateau, near Chattanooga, Tennessee. It is virtually unknown and is remarkably different from the common types of sinkholes. In spite of its situation 800 feet above limestone beds, it is thought to have originated by collapse of hundreds of feet of strata into a large cavern. Description and preliminary treatment of the theory of origin are here offered.

INTRODUCTION

A pit-like sinkhole, more than 300 feet in diameter and perhaps equally deep, vertically walled by massive beds of sandstone, underlain by shales, having no soluble limestone strata closer than 800-odd feet beneath, situated on top of a flat plateau within a few hundred feet of the edge of the escarpment, and permanently occupied by a beautiful deep-blue lake, is a geologic phenomenon of unusual character. Yet such is the basin of Montlake, Hamilton County, eastern Tennessee. Few scientists have ever seen or heard of it. The writer's reaction upon first visiting this unusual feature was one little short of amazement. It is strange that such a natural wonder has not been described in scientific literature, and that it is so little known, even in its own state. The *United States Geological Survey Folio 6*, covering the Chattanooga quadrangle, makes no mention of it; but the included map shows a fair-sized, unnamed lake, incorrectly mapped with respect to the deep sinkhole.

Montlake has recently become a subject of considerable controversy in Tennessee through an effort to convert it, along with a considerable tract of surrounding plateau land, into a state park. The writer has visited Montlake several times, and has made a preliminary survey and study of it. The purpose of this paper is to call the attention of the scientific world to the phenomenon, to describe it and the surrounding geologic conditions briefly, and to offer a tentative explanation of its origin. It is recognized that final and compre-

hensive treatment could be offered only after thorough detailed study and careful mapping.[1]

LOCATION AND DESCRIPTION

Montlake is situated on the Cumberland Plateau, 15 miles north, slightly east of Chattanooga, Tennessee, and 21 miles southwest of Dayton. It is 2 miles west of the town of Daisy, and less than $\frac{1}{4}$ mile from the Cumberland escarpment, which marks the abrupt eastern edge of the plateau (Fig. 1). A secondary road leads to within a short distance of it. The immediate approach is over a nearly flat, sandy, wooded surface. Not even a faint suggestion prepares one for the phenomenon, when suddenly one reaches the immediate rim of the shaft-like pit and looks directly down nearly 150 feet upon the blue water of the lake (Fig. 2).

The sinkhole is elliptical in shape. The greatest diameter at water level is 390 feet, in a direction N. 70° W.—S. 70° E., whereas the minimum diameter is approximately 250 feet. The sandstone wall three-fourths of the way around is relatively smooth and practically vertical, produced by the breaking off of blocks along slightly curved joints (Fig. 2). At one place there is a decided overhang near the rim. At the southeast side the pit is bordered by a jagged talus of fallen sandstone blocks where one can descend to the water's edge. The rock wall rises 130 feet above the mean level of the lake.

The depth of the water is unknown. However, the deep-blue color of the lake, the verticality of the wall continuing to concealed depths below water level, and the complete submergence of talus blocks around all but a small sector, suggest downward continuation of the pit to a considerable depth, perhaps as much as 100 feet or more. Final study of the feature should include careful soundings. Local residents claim knowledge of a depth around 150 feet. Assuming a water depth of 100 feet, the sinkhole has a vertical dimension of 230 feet.

The wall rock is sandstone and conglomeratic sandstone of the

[1] The feature was first called to the writer's attention by Mr. Walter F. Pond, State Geologist of Tennessee, who visited the site with the writer, and who has contributed valuable suggestions utilized in this paper. (The studies leading to this writing have been made incidentally, while conducting the summer field course in geology for the Ohio State University.)

Sewanee (Lower Pottsville) formation. It is mainly hard and massive, with marked bedding planes and a few cross-bedded layers. Some 800 feet of clastic strata (sandstone and shale) lie immediately

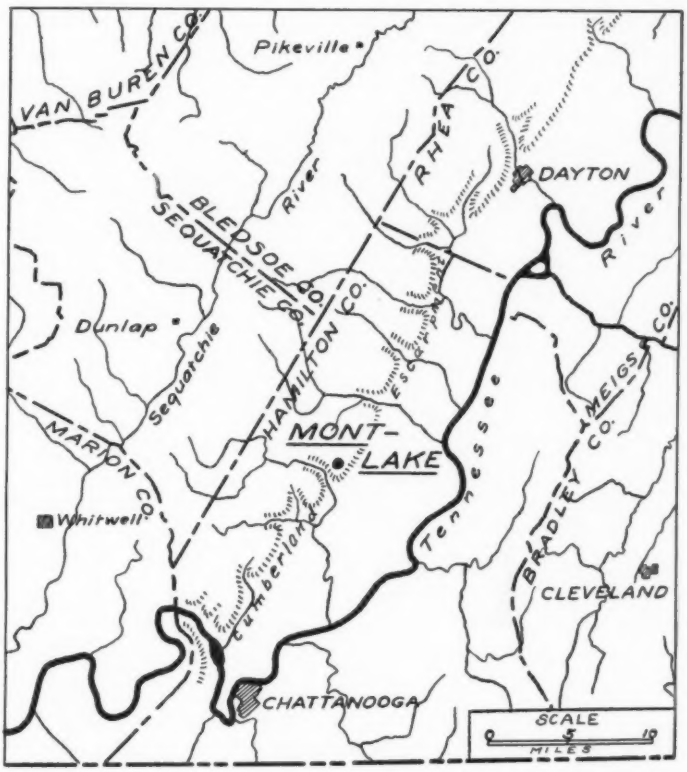

FIG. 1.—Map of a portion of eastern Tennessee, showing the location of Montlake

beneath. Under these are the thick Upper Mississippian limestones (Fig. 3).

There is a much smaller sinkhole about 300 feet to the southeast, separated from Montlake by a ridge of slumped sandstone blocks. It has a diameter of 100 feet or more, a depth of perhaps 30–40 feet, and is dry. Adjoining this at the southeast is another, yet smaller,

depression which is also dry. Beyond this is a shallow upland valley running to the plateau's edge in a direction S. 60° E.

PHYSIOGRAPHIC SETTING

One of the significant aspects of Montlake is its perched position on top of the Cumberland Plateau. This particular part of the plateau is frequently referred to as Walden Ridge, being separated from

FIG. 2.—View of Montlake, taken from the southeast side, showing the high, precipitous wall of massive sandstone. The topmost point on the vertical face in the background is 130 feet above the water.

the main plateau by the deep Sequatchie Valley 10 miles to the west. It is relatively flat-topped, held up by nearly horizontal, resistant sandstone and conglomerate beds, at elevations ranging from approximately 1,600 to 1,800 feet. The rim of the sinkhole has an elevation of 1,630 feet at the highest place, whereas the lake has a mean elevation of about 1,500 feet. The eastern edge of the plateau is marked by the abrupt Cumberland escarpment which, because of its steepness and height of nearly 1,000 feet, is one of the most prominent topographic features of eastern Tennessee. No farther than $\frac{1}{5}$ mile back from the nearest point on the escarpment lies Montlake (Figs.

1 and 3). East of the plateau is the Tennessee section of the Valley and Ridge Province, the nearby lowland tracts of which range from 700 to 740 feet above sea-level. The Tennessee River at the nearest point 6 miles away has a low-water elevation of about 640 feet. North Chickamauga Creek, a tributary to the Tennessee, is the most important stream close to Montlake. It has a re-entrant valley deeply cut westward into the plateau a fraction of a mile south of the Montlake site. This stream lies more than 900 feet below the rim of the sinkhole.

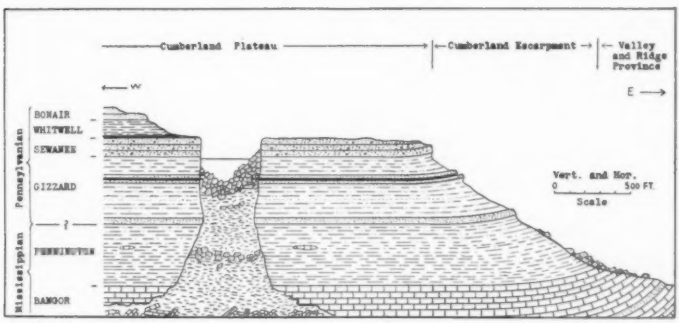

FIG. 3.—Sketch of a generalized cross section through Montlake (looking north-northeast), showing relationships of the sinkhole to the physiography, stratigraphy, and structure.

A feature which commands special mention is a large spring which emerges beneath sandstone talus blocks on the lower slopes of the escarpment about $\frac{1}{3}$ mile to the east of Montlake. The elevation of the spring is 1,035 feet—a position nearly 500 feet lower than the water level in the sinkhole, and nearly 300 feet higher than the foot of the escarpment. There is a second but smaller spring in a similar topographic position a short distance to the northeast. One might surmise that escape-water from Montlake contributes to the flow of these springs.

There are no known large limestone caverns in the immediate vicinity. The thick Upper Mississippian limestones, known to be cavernous elsewhere, have limited outcrops in the lowlands just south of North Chickamauga Creek. These strata contain the well-known Lookout Mountain caverns near Chattanooga, where underground chambers nearly 100 feet high exist.

STRATIGRAPHIC AND STRUCTURAL CONDITIONS

The most perplexing and peculiar aspect of Montlake is the stratigraphic and lithologic situation. Large sinkholes of collapse origin are commonplace within *limestone* beds. There are also on record a few cases of sinkholes in clastic strata which have crashed into cavernous limestones either immediately or within a few feet beneath. But Montlake sinkhole is some 800 feet above any limestone. It is, furthermore, spectacular in being unusually large, remarkably deep, and occupying a position within extra-stout, massive sandstone beds (Fig. 3).

A generalized stratigraphic section for the escarpment and plateau in the Montlake vicinity is given in Table I.

TABLE I

	Feet
Pennsylvanian (Lower Pottsville):	
Rockcastle conglomerate	150 to 200
Vandever shale	150
Bonair sandstones	150
Whitwell shale (Richland coal at the base)	125
Sewanee conglomerate	100 to 125
Gizzard formation (sandstones, shales, and coals)	400 to 500
Upper Mississippian:	
Pennington shale	400
Bangor (restricted) limestone	350

Both to the north and south along the escarpment and adjoining lowlands the following older Mississippian formations crop out in addition to those listed in Table I:

Hartselle sandstone
Gasper oolite
Ste Genevieve limestone
St. Louis limestone
Warsaw formation
Ft. Payne chert
Chattanooga shale (of doubtful age, at least in part)

An excellent section containing 700 feet of nearly continuously exposed strata may be studied and measured along the escarpment

at the abandoned inclined narrow-gauge railway, the top of which is but $\frac{1}{3}$ mile S. 21° W. of Montlake. Years ago the railroad served for lowering coal which was extensively mined on top of the plateau. The abandoned mining sites furnish one of the interesting spectacles in the Montlake area. At the above-mentioned exposure the strike of the beds is N. 75° E.; the dip 5° to 7° NW. The strata flatten quickly under the plateau. A detailed description of the section is of no particular value in this study.

In the Montlake region the brink of the escarpment and the surface of the plateau a little farther westward are developed upon the Sewanee—a 125-foot formation of massive sandstone and conglomerate. (This is the upper unit of the "Lookout sandstone" of early geologists.) Thus, the sinkhole above lake level is encircled by beds of this formation (Fig. 3). Immediately to the west and above the rim of the sinkhole are the shales of the Whitwell, with the important Richland coal at the base. To the west the plateau next rises onto the coarse, whitish, cross-bedded sandstone of the Bonair group. Some distance away the upland reaches the bold Rockcastle conglomeratic sandstone.

Beneath the lake level the sinkhole is developed in the upper sandstones and shaly sandstones of the Gizzard formation. At the above-mentioned section along the abandoned inclined railway, over 450 feet of shales and sandstones of the Gizzard formation crop out. Beneath this outcrop is at least 400 feet of soft, argillaceous shale of the Pennington. This shale is in turn underlain by the cavern-forming Bangor (restricted) limestone. Thus it is seen that the surface of Montlake lies more than 800 feet above any soluble, cavern-forming rock.

Along the escarpment the strata are turned upward toward the folded and faulted Valley and Ridge Province to the east. Varying amounts of metamorphism are displayed in the inclined beds. Some of the sandstones are quartzitic. One of the quartzitic members of the Gizzard offers the peculiarity of a few distinct stylolite-seams prominently developed along the bedding planes. Some of the shales have developed slight schistosity. The upturned beds at the escarpment flatten out in a short distance under the plateau, so that at Montlake the rocks are practically horizontal and not metamor-

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phosed. To the west the strata rise upon approaching the Sequatchie Valley and, therefore, crop out at elevations considerably higher than along the Cumberland escarpment. A great thrust fault, striking generally N. 30° E., prevails along or near the foot of the escarpment across most of the state. This structure, however, has no direct bearing upon the origin of Montlake. There is no fault at the site of Montlake and the adjoining smaller sinkholes.

PROBABLE ORIGIN

After balancing the field evidence displayed at Montlake against various hypotheses, there seems to the writer to be but one conclusion—the sinkhole resulted from collapse into a subterranean cavern, initiated in the soluble limestone 800 or more feet below. It is not likely that the entire collapse throughout all the intervening strata occurred suddenly and at one time. First a limestone cavern may have developed at or near the top of the Bangor limestone. Collapse of some of the immediately overlying rock would expose the soft and weak shales of the Pennington above. These shales in turn may have been gradually stoped into the underlying cavern. If there were a moving stream, part of the clay-shales could have been carried away as mud from the bottom of the shaft-like room, thus preserving the room for a time. Successive collapses of the overlying jointed sandstones and shales occurred until finally, after subsurface collapsing had gone on to the point of sufficiently removing the support, the capping Sewanee strata crashed in, filling the room and producing the now observed sinkhole at the top. Subsequent breaking off of sandstone blocks along joints has no doubt enlarged the pit.

CONCLUSIONS

The foregoing description and suggested origin of Montlake may lead one to delve into numerous questions and controversial problems. Many details have not been examined in the field, and numerous issues have been avoided in this writing. Complete analysis of the feature would require time-consuming field studies, including accurate surveying, mapping, and sounding of the lake. This paper is offered as a preliminary report to bring to the attention of geologists the existence of such a spectacular and unusual sinkhole, to describe it briefly, and to suggest its manner of origin.

NOTES ON THE SKULL OF *YOUNGINA CAPENSIS* BROOM

EVERETT CLAIRE OLSON
University of Chicago

ABSTRACT

A new skull of *Youngina capensis*, in which the palate, brain case, and quadrate region are preserved in excellent condition, is figured and described in detail. Several previously unknown features of the skull strengthen the conclusion that this form is on or near the line of ancestry of the Squamata and Rhynchocephalia.

INTRODUCTION

The first description of *Youngina*, based on the type specimen, appeared in 1914.[1] Broom's original description, giving the specific name of *gracilis*, had been written previously but did not appear in print until a few months later.[2] In the first paper to be published, the specific name of *capensis* was used, and it is this name which must stand. In 1929 Watson[3] figured for the first time some of the structure of the palate and brain case of this specimen.

The type specimen of *Youngina capensis*, which consists of a skull and lower jaws, originally belonged to the American Museum of Natural History, being listed as specimen No. 5561. Subsequently it has come into the possession of the British Museum.

Since the discovery of the type in 1912, three other specimens have been found. Two of these have come into the hands of Broom at the Pretoria Museum. Both were collected from the *Cistecephalus* zone of the Upper Permian at New Bethesda, South Africa, only a few yards from the spot at which the type was found. From one Broom has been able to give a fairly complete account of the postcranial structure, and from the other he has worked out and described much of the dermal surface of the skull and has thrown some light on the composition of the quadrate region. From a study of both specimens

[1] R. Broom, "A New Thecodont Reptile," *Proc. Zoöl. Soc. London, 1914*, pp. 1072–77.

[2] R. Broom, "Catalogue of Type and Figured Specimens of Fossil Vertebrates in the American Museum of Natural History, II. Permian, Triassic and Jurassic Reptiles of South Africa," *Amer. Mus. Nat. Hist. Bull. 25*, Part II (1915), pp. 161–62.

[3] D. M. S. Watson, "Reptiles," *Encyclopaedia Britannica*, (14th ed., 1929), Vol. XIX, pp. 180–200.

Broom[4] has been able to describe in a general way the structure of the palate.

The third specimen (University of Chicago, No. 1528), which is described in this paper, consists of a skull and lower jaws. It was collected in 1929 by Mr. P. C. Miller and Dr. A. S. Romer from the *Cistecephalus* zone on the Toverwater farm a few miles southeast of Murraysburg, South Africa. The specimen is in excellent condition, being practically complete and only slightly distorted. It has been possible, by painstaking preparation, to reveal many heretofore unknown facts about the palate, brain case, and quadrate region. Certain of these features are important in a consideration of the phylogenetic position of this upper Permian diapsid reptile.

I wish to express my thanks to Dr. A. S. Romer, Mr. L. I. Price, and Dr. T. White for their aid in the interpretation of certain features of the brain case of this specimen.

PALATE

The palate of *Youngina capensis* (Fig. 1*A*) is quite generalized and is similar in general composition to the palates of *Iguana* and *Sphenodon*. It is marked by a series of fenestrae consisting of (1) long internal nares, (2) a vacuity between the prevomers, (3) moderately large infraorbital vacuities, and (4) a small interpterygoidal vacuity.

Prevomers, palatines, pterygoids, and ectopterygoids are present in the palate. The prevomers are narrow, splintlike bones which come in contact with the premaxillaries anteriorly, the palatines laterally, and the pterygoids posteriorly. The two prevomers are separated by a rather large, V-shaped vacuity and encompass the anterior tips of the long internal nares just posterior to the premaxillary bones. They bear no palatal teeth.

The palatines are large bones which surround the major portion of the internal nares, reach back to the anterior and median margins of the infraorbital vacuities, and join the pterygoids laterally by means of sutures. These sutures cannot be definitely identified in the posterior portion of this junction. There is a row of about ten small, conical teeth on each of the palatines just medial to the infraorbital

[4] R. Broom, "Further Evidence on the Structure of the Eosuchia," *Amer. Mus. Nat. Hist. Bull. 51* (1924), pp. 67–76.

vacuities, and there are two rows of very small teeth bordering the prevomers and the internal nares.

The pterygoids are long, slender bones which pass from the posterior margin of the prevomers back to the quadrate bones to which they were firmly fixed. From the posterior terminations of the infra-

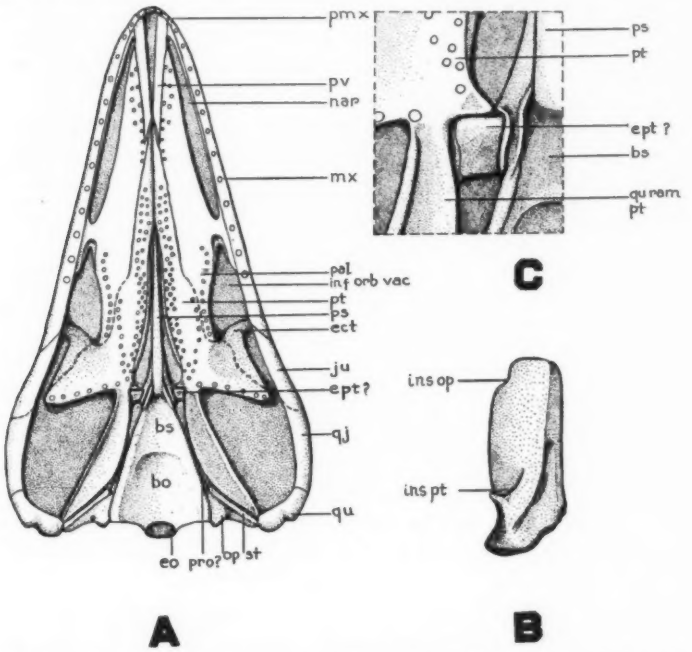

FIG. 1.—The skull of *Youngina capensis*. *A*, palate and brain case, ventral aspect, ×3:2; *B*, right quadrate bone, posterior aspect, ×3:1; *C*, joint between pterygoid and basisphenoid showing intervening element, ×7:1; *bo*, basioccipital; *bs*, basisphenoid; *ect*, ectopterygoid; *eo*, exoccipital; *ept*, epipterygoid; *inf orb vac*, infraorbital vacuity; *ins op*, insertion of opisthotic; *ins pt*, insertion of pterygoid; *ju*, jugal; *mx*, maxillary; *nar*, internal naris; *op*, opisthotic; *pal*, palatine; *pmx*, premaxillary; *pro* proötic; *ps*, parasphenoid; *pt*, pterygoid; *pv*, prevomer; *qj*, quadratojugal; *qu*, quadrate; *qu ram pt*, quadrate ramus of the pterygoid; *st*, stapes.

orbital vacuities to the prevomers they are in contact with the palatines. The pterygoids are separated for a short distance in the midline by the interpterygoidal vacuity but are in contact anterior to it.

Back of this vacuity there are strongly developed transverse processes which reach very nearly to the lateral margins of the skull. Small ectopterygoids lie lateral to, and in front of, the transverse processes and pass out to join the dermal surface of the skull at the junction of the maxillaries and the jugals. The quadrate rami of the pterygoids are broad and long.

Teeth are present on the pterygoids along the median margins, where they are arranged in two irregular rows, along the posterior part of the junction of the palatines and pterygoids in a single row, and along the transverse processes. The articulation of the pterygoids with the brain case is accomplished by a small block of poorly ossified bone or cartilage. The details of this structure, not recognized heretofore in *Youngina*, will be taken up in connection with the brain case.

BRAIN CASE

The brain case of *Youngina capensis* possesses several interesting features and is important in the consideration of the phylogenetic position of the animal.

The foramen magnum is enclosed by the basioccipital ventrally, the exoccipitals, which are separated from the basioccipital by distinct sutures, laterally, and the supraoccipital dorsally. The basioccipital, which forms the posterior portion of the floor of the brain case, is broad and deeply concave on the ventral side. There is no suture indicating the separation of this bone from the more anterior basisphenoid.

The basisphenoid, which is also concave ventrally, continues forward, becoming narrow, and passes under the parasphenoid. The latter is very long and slender and runs at least as far forward as the anterior termination of the interpterygoidal vacuity. It appears to pass forward under the pterygoids, which are closely applied to each other anterior to the vacuity. The posterior portion of the parasphenoid is rather broad and covers the anterior part of the basisphenoid. Just how far back over the latter the parasphenoid extends cannot be determined.

Dorsal to the parasphenoid is a bone which is continuous with the basisphenoid and which gives the appearance of being a very long rostrum of the latter. Although this dorsal bone is fused to the parasphenoid, it is readily distinguished by texture and by the fact that it

does not follow the established curvature of the parasphenoid. There is no suture between the two. Its forward extension cannot be followed for more than half the length of the rostrum of the parasphenoid, because the left pterygoid has been pushed over the parasphenoid at this point and the anterior portion of the interpterygoidal vacuity is too small to permit investigation. The posterior part of this bone is flanked by the anterior part of the basipterygoid process of the basisphenoid.

The condition described above appears to be somewhat similar to that found in various primitive reptiles in which the presphenoid area has been studied in detail. An ossification in the area is definitely known in such cotylosaurs as *Labidosaurus* and such pelycosaurs as *Ophiacodon*. The condition in *Youngina* differs from that in either of these in that the element is fused to the parasphenoid and basisphenoid. The ossification seems to have taken place in a cartilage which is homologous to the so-called "presphenoid cartilage" in lizards and *Sphenodon*. It probably represents the sphenethmoid bone, an element not previously identified in *Youngina*. The homologies with the presphenoid, orbitosphenoid, and ethmoid bones of mammals are uncertain.

The presence of the sphenethmoid seems to be of little phylogenetic significance except that it is another indication of the primitive nature of *Youngina*. The condition in lizards and *Sphenodon* is quite similar except that the presphenoid cartilage has failed to ossify.

A most interesting feature of the brain case and palate of *Youngina*, and one which does appear to be of considerable phylogenetic significance, is the joint between the basisphenoid and pterygoid (Fig. 1*C*). This joint is accomplished by a small, nearly unossified block which lies between the two bones. There is no contact between the pterygoid and the basisphenoid. The basisphenoid process of the pterygoid bounds the lateral surface of the block and extends a short way onto its anterior margin; the basipterygoid process of the basisphenoid covers the median face of the block and also extends slightly onto the anterior face. A portion of the basipterygoid process extends forward a short distance along the sphenethmoid, to which it is fused.

The homology of the element between the pterygoid and basisphe-

noid is uncertain. The block is similar in position to the foot of the epipterygoid which lies between the pterygoid and basisphenoid in such primitive reptiles as *Captorhinus*, *Labidosaurus*, *Ophiacodon*, etc.[5] However, it is partially unossified. On the other hand, it appears quite like a cartilaginous element which occupies the same position in certain Lacertilia and *Sphenodon* but which is not connected with the epipterygoid in any stage of the development of these forms. It is impossible, without sectioning, and thus destroying the specimen, to determine whether or not the element in *Youngina* is connected with the epipterygoid.

Several suggestions have been made regarding the homology of the cartilage element in the lacertilians and *Sphenodon*. Parker[6] appears to have been the first to note its presence, but he paid little attention to it. Howes and Swinnerton[7] described and figured a similar element in *Sphenodon*, calling it the "meniscus pterygoideus" because of its close connection to the pterygoid and its similarity to the meniscus mandibuli of mammals. Broom[8] cited evidence based on the embryology of the Lacertilia to show that this cartilage is a persistent mesopterygoid. Watson[9] described what he considered to be a similar element in *Seymouria*. However, examination of new material has shown that no such element is present.[10] He suggested that the element might represent an autogenous basipterygoid process following the evidence of Gaupp (1900) that the basipterygoid process contained independent centers of ossification in the Lacertilia.

There is no definite proof that any of these conclusions is correct. Broom's hypothesis of a persistent mesopterygoid, as he presents it, would seem to indicate that this element has been carried through the evolutionary series from the crossopterygians to the Lacertilia

[5] L. I. Price, personal communication.

[6] W. K. Parker, "On the Structure and Development of the Skull in the Lacertilia," *Phil. Trans. Roy. Soc. London, 1879*, p. 612 and Pl. 45, Fig. 4.

[7] G. B. Howes and H. H. Swinnerton, "On the Development of the Skeleton of the Tuatera, *Sphenodon punctatus*, with Remarks on the Hatching and the Hatched Young," *Trans. Zoöl. Soc. London*, Vol. XVI (1901), pp. 1–86.

[8] R. Broom, "On the Persistence of the Mesopterygoid in Certain Reptilian-Skulls," *Proc. Zoöl. Soc. London, 1922*, pp. 455–60.

[9] D. M. S. Watson, "On *Seymouria*, the Most Primitive Known Reptile," *ibid., 1918*, pp. 267–301.

[10] A. S. Romer and T. White, personal communication.

and Rhynchocephalia, with little change except a diminution in size and a loss of ossification. It is difficult to believe that an element so persistent as to be present in living lacertilians and *Sphenodon* could be unknown in all the more primitive tetrapoda and still be a remnant of the mesopterygoid present in *Eusthenopteron*.

However, there are certain implications involved in Broom's hypothesis which are not brought out in his discussion. Watson[11] has pointed out that the mesopterygoid of *Eusthenopteron* is homologous with the epipterygoid of the Tetrapoda. If it may be assumed that the basal process of the epipterygoid has become separated from the ascending ramus of this bone and has lost its ossification, it would seem probable that the "meniscus" of the Lacertilia and *Sphenodon* is homologous with the foot of the epipterygoid, and hence with part of the mesopterygoid. At no stage in the embryologic development of these two types is there any contact between the "meniscus" and the ascending ramus of the epipterygoid, but conceivably such a connection may have existed in ancestral types.

The unossified or cartilaginous element in *Youngina* has tentatively been identified as the foot of the epipterygoid. Its position and composition indicate that it may also be homologous with the cartilage "meniscus" of the Lacertilia and *Sphenodon*. The suggestion is that it represents a stage intermediate between the condition in the cotylosaurs and the Squamata and Rhynchocephalia.

There is little that can be added to the description of the otic region from the study of the present specimen, for this part of the skull has suffered considerable breakage. The opisthotic, which has been displaced somewhat from its original position, is a large bone which passes laterally from the supraoccipital and exoccipital to the tabular and the dorsal margin of the quadrate, where it rested in a shallow notch (Fig. 1*B*). Anterior to it lies the proötic which can be but doubtfully identified. Along the anterior margin of the opisthotic runs a very slender stapes, a bone previously not identified in *Youngina*. No details of this bone can be made out. It appears to terminate at the contact of the proötic and opisthotic, and presumably ran to the quadrate.

[11] D. M. S. Watson, "The Evolution and Origin of the Amphibia," *Phil. Trans. Roy. Soc. London*, Vol. 214*B* (1925–26), pp. 189–257.

QUADRATE REGION

The quadrate region has been badly damaged or destroyed in the three specimens which have been described previously. In the present specimen it is complete on one side, the right. Crushing and breakage, however, have displaced certain elements from their original positions. The quadrate bone has been shifted somewhat dorsally and medially but has retained its natural contact with the lateral dermal bones of the skull. The pterygoid has been displaced slightly from its original position on the quadrate but is still in contact with this bone. The opisthotic has been moved considerably downward. None of the bones of the area have been displaced to such an extent that the original relationships of the quadrate are obscured.

The quadrate bone (Fig. 1*B*) is relatively large, measuring approximately 9.5 mm. from top to base and 4 mm. at the point of greatest width. The posterior surface of the bone, the only surface which can be exposed, consists of a large, flat inner face directed medially at an angle of about 45° and a smaller outer face directed posteriorly. These two faces are separated by a ridge which passes from near the outer edge of the top of the bone diagonally down to a point just above the base. The inner face is marked by a small notch on the dorsal tip and a shallow depression with a shelf below near the base. The outer face has a rather deep depression on the lower portion. The basal part of the bone flares somewhat to form an enlarged area for the articulation of the lower jaw.

The outer margin of the quadrate is in close contact with the quadratojugal below and the squamosal above. The tabular passes down about 2.5 mm. over the dorsal margin of the quadrate in the specimen. However, if the bones were restored to what appears to have been their original positions, the tabular would pass only a short way over the dorsal margin of the quadrate, and would probably be in contact with it. The opisthotic appears to have rested in the small dorsal notch of the inner face, and the pterygoid was fixed in the more ventral depression of this face. The quadrate was firmly held in position and was not moveable.

DISCUSSION

There are two principal, opposing hypotheses regarding the origin of the Squamata: (1) the group arose from an *Araeoscelis*-like form

proposed by Williston; and (2) the Squamata had their origin among the diapsids through *Youngina* and a *Sphenodon*-like rhynchocephalian, proposed by Broom. It is unnecessary to summarize the arguments for and against the two hypotheses, since they have been adequately treated by Williston[12] and Broom.[13] Both have points in their favor, but the evidence appears to support the diapsid origin more strongly.

The structures of the skull of *Youngina* described in the present paper lend strong support to Broom's conclusion that *Youngina* was ancestral to the Squamata, but do not support so strongly the idea that *Sphenodon* may be a persistent representative of an intermediate stage. *Youngina* proves to be more similar to a generalized lacertilian such as *Iguana* than to *Sphenodon*.

The palate of *Youngina* is much like that of *Iguana* except for slight differences in the disposition of the component bones and the absence of certain series of palatal teeth in *Iguana*. The length and position of the internal nares are very similar. The relative size, shape, and boundaries of the infraorbital vacuities check closely. The pterygoids of *Youngina* are entirely similar to those of *Iguana* so far as the quadrate ramus, the transverse process, the basisphenoid process, and the relation to the infraorbital vacuity are concerned. In both forms they extend forward to the prevomers; but in *Iguana* this relationship is obscured on the ventral surface of the palate by the palatines, which have grown over the pterygoids to meet in the mid-line. The palatines of the two forms differ only in this overgrowth in *Iguana* and in the presence of palatal teeth in *Youngina*. The ectopterygoids are similar in composition and disposition. The prevomers are essentially alike in the two forms, but in *Iguana* they have expanded somewhat laterally and posteriorly to cover the anterior ends of the palatines and to bound the internal nares.

So far as the structure of the brain case of *Youngina* has been determined, it is quite similar to that of *Iguana*. The basioccipitals, exoccipitals, supraoccipitals, basisphenoid, and parasphenoid com-

[12] S. W. Williston, "The Osteology of Some American Permian Vertebrates," *Jour. Geol.*, Vol. XXII (1914), pp. 364–419.

[13] R. Broom, "On the Classification of Reptiles," *Amer. Mus. Nat. Hist. Bull. 51* (1924), pp. 39–65; "On the Origin of Lizards," *Proc. Zoöl. Soc. London, 1925*, pp. 1–16.

pare very closely. The basipterygoid processes differ somewhat in that the process in *Youngina* is extended forward along the ossification identified as the sphenethmoid. As pointed out in the description, the ossification of the latter seems to be of little phylogenetic significance, for a comparable cartilage is present in the Lacertilia and *Sphenodon*.

The unossified element between the basisphenoid and basipterygoid processes in *Youngina* may prove to be of the utmost importance in placing this form as an ancestor of the Squamata and Rhynchocephalia. However, until it is possible to show the exact condition of this element in *Youngina* and the homology of the element in the Lacertilia and Rhynchocephalia, it is not possible to state definitely that the condition in *Youngina* represents a stage intermediate between the cotylosaurs and these two groups.

An element between the basipterygoid and basisphenoid processes has been definitely identified only in certain Lacertilia and *Sphenodon* among living reptiles and in certain cotylosaurs, pelycosaurs, and *Youngina* among fossil reptiles.[14] Unless an element has developed independently in this position in these groups, which seems unlikely, there is a strong suggestion that *Youngina* is closely related to the Cotylosauria on one hand and the Squamata and Rhynchocephalia on the other.

There is nothing known in the otic region of *Youngina* to bar it from a position ancestral to the Lacertilia. The quadrate bone of the former is quite similar to that of *Iguana* and other lizards and needs but slight changes in shape to become an exact replica of the typical lacertilian quadrate. Broom[15] and Parrington[16] have discussed the changes which must occur in the quadrate and temporal regions of a primitive diapsid to produce the condition found among the Squamata, and have cited evidence to show that such changes probably have occurred.

[14] A similar element has been identified and since been shown to be lacking in *Seymouria* (see p. 528), and there is a suggestion of such an element in *Ichthyosaurus* (Sollas, "The Skull of Ichthyosaurus, Studied in Serial Sections," *Phil. Trans. Roy. Soc. London*, Vol. 208*B* [1916]).

[15] R. Broom, "On the Classification of Reptiles," *loc. cit.*, pp. 39–65.

[16] F. H. Parrington, "On *Prolacerta broomi*, and the Origin of Lizards," *Ann. and Mag. of Nat. Hist.*, 10th ser., Vol. XVI (1935), pp. 197–205.

The new evidence presented in this paper, combined with that previously given by Broom and others, seems to indicate that *Youngina* was closely related, if not ancestral, to the Squamata.

A point-for-point check of the palate, brain case, and quadrate region of *Youngina* and *Sphenodon* indicates that these forms were similar in many respects. The disposition of the prevomers, palatines, and anterior portions of the pterygoids in *Sphenodon* is very similar to that in *Youngina*. The brain cases of the two are also essentially alike, so far as the structure of *Youngina* has been made out. However, the internal nares, the infraorbital vacuities, the quadrate rami of the pterygoids, and the quadrate bones of *Sphenodon* are somewhat farther from the pattern in *Youngina* than are the corresponding structures in *Iguana*. It appears that *Sphenodon* lies somewhat farther from the line of ancestry of the Squamata than does *Youngina*, although both the Lacertilia and Rhynchocephalia probably developed from the Eosuchia.

Only *Captorhinus*, among the Cotylosauria, has been studied in sufficient detail to permit a legitimate comparison with *Youngina*. Price [17] has given an excellent and accurate account of the brain case of this form. The ventral contours of the brain case, the foramina so far as they have been made out in *Youngina*, the quadrate bone, and the position of the foot of the epipterygoid are quite similar in *Captorhinus* and *Youngina*. The stapes, which is very large in *Captorhinus* and small in *Youngina*, the extent of the parasphenoid bone, and the condition of the sphenethmoid bone are somewhat different. However, there seems to be nothing to indicate that *Youngina* may not have arisen from some generalized cotylosaur.

There is little that can be said about the relationships of *Youngina* to the other diapsid groups, since the details of the palates and brain cases of the most primitive members of the various groups are inadequately known. So far as can be told, there is nothing in the structure revealed in the skull of *Youngina* to exclude this form from the ancestry of the primitive protosuchians; but there is little positive evidence pointing to such a relationship.

[17] L. I. Price, "Notes on the Brain Case of Captorhinus," *Proc. Boston Soc. Nat. Hist.*, Vol. XL (1935), pp. 377–86.

REVIEWS

On the Dermal Bones of the Head in Labrinthodont Stegocephalians and Primitive Reptilia. By G. SÄVE-SÖDERBERGH. Meddelelser om Grønland, Bd. 98, Nr. 3. Copenhagen: C. A. Reitzels Forlag, 1935. Pp. 211; figs. 68; pls. 15. Kr. 11.00.

This interesting work is divided into two portions: a description of new labyrinthodont material from the "Eotriassic" of Greenland and—longer, more stimulating, and more provocative—a comparative study of the dermal skull elements of primitive tetrapods, leading to a reclassification of these forms and of tetrapods in general.

In comparative anatomy the basic principle of nomenclature is the application of human or other mammalian names to structures in lower types reasonably believed homologous with those of mammals. When homologies are in doubt, the temporary erection of an independent nomenclature may be undertaken, this being dropped when the problem is resolved. As regards the skull roof of tetrapods, the homology of the bones has been fairly well established, and in most cases mammalian names are readily applicable to amphibian and reptilian elements. As far back as 1917 a special committee of the Paleontological Society was able to report practical unanimity as to homologies and essential agreement as to terminology.

To carry the mammalian homologies down to the bony fish groups has proved a more difficult task: the phylogenetic gaps are wide and many attempted comparisons of dubious validity. Thus Stensiö was justified some years ago in establishing an independent fish nomenclature, with the implication that the measure was a temporary one, to be abandoned when the gaps were closed. In the present work Säve-Söderbergh claims to have closed these gaps, and that with two minor exceptions all lower tetrapod elements "can be homologized, with a high degree of certainty, with definite bones, or parts of bones, of the Crossopterygians." If this claim is justified, it would seem that we are at last in a position to carry down the accepted tetrapod nomenclature to the fishes.

Exactly the reverse course is adopted by Säve-Söderbergh. He uses a modification of Stensiö's fish terminology and applies this to amphibian and early reptilian skulls. It would appear that he is unacquainted with

the literature on higher tetrapods (the committee report mentioned above is not even cited in his bibliography), and in contrast to his certainty with regard to his new findings, the work of Broom, Case, Gregory, von Huene, Watson, and Williston (to cite a few) is dismissed with the statement that the customary terminology is not used because "there are yet too many questions unsolved."

The result of this reversal of usage is a highly confused situation. Stensiö used mammalian terms in obviously arbitrary senses. He further regarded the presence of a single element in an area elsewhere covered by two or more bones as indicating fusion, whereas most workers believe that such cases have generally resulted from the suppression of minor centers. This has led to the introduction of compound terms for many elements. Such compounds are applied by the present author to tetrapod elements which (as may be seen in great measure from his own figures) have ossified from a single center and to which the implication of compound origins can have only a mystical significance.[1]

In their journey down to the fish and back up again to tetrapods the familiar terms have undergone strange metamorphoses. For example, the lower tetrapod homologue of the mammalian maxilla has never been questioned. Säve-Söderbergh, however, calls this element a "lachrymomaxillary," implying that there has been fusion with a "lachrymal." But by definition the lachrymal is an independent mammalian element adjacent to the maxilla, and carrying the tear duct. We thus seem forced to assume that the lachrymal leads a double life, existing both as a concrete object and as a hypothetical portion of the maxilla. The author appears to avoid this by calling the reptilian lachrymal an "antorbital" and denying its homology with the mammalian element. This is done by referring to the older work of Gaup, whose view is now held only by one or two German workers; he is forced to ignore completely (or is unaware of) the most important work on the subject, that of Gregory, and omits any reference to the fact that the lachrymal duct is definitely known to exist in many instances in the bone he labels "antorbital."

The author's phylogenetic conclusions in general rest on slim bases. For example, a major subdivision of the tetrapods is grounded on the assumption that the amphibians are diphyletic, the salamanders de-

[1] Säve-Söderbergh is unable to demonstrate a fusion in any instance. His best example (pp. 10, 45) is the supposition that a jog in the outline of the parietal of *Trimerorhachis* indicates a double origin for that element. But this is based on Williston's figure of the skull; Case's more recent work (1935) shows that this feature is nonexistant.

scended from a lungfish stock, all other forms from crossopterygian-like ancestors. Such a radical departure merits consideration only if backed by substantial evidence. This is lacking. It is supported merely by this statement: "As demonstrated, for instance, by Wintrebert (1910, 1922*a*, *b*) and, quite recently, by Holmgren (1934) the Urodeles are very nearly related to the Dipnoi and apparently not so much to the Crossopterygii." In point of fact, no radical claims are made in the papers cited. Wintrebert, from a study of the palate, believes that urodeles have evolved separately from the fish stage, but is little concerned as to the fish groups involved; Holmgren believes the urodele limb indicates descent from a form with an elongate archipterygium, but recognizes that this is found in the Crossopterygii as well as Dipnoi.

The remaining tetrapods are classified almost exclusively upon the dermal roofing elements. It is not improbable that certain of the phyletic lines advocated by Säve-Söderbergh are correct, but little weight can be placed upon a phylogeny based solely upon a set of structures so obviously open to environmental influence.

In his classification, the author's tendency to give names to each branch of a dichotomy in his hypothetical family tree results in the elevation of the urodeles to a class, equal to all other tetrapods put together, while the mammals are demoted to an order, and a doubful one, at that.

Dr. Säve-Söderbergh's essay is a stimulating one, but his phylogenetic conclusions are for the most part open to serious doubt, his scheme of classification impractical, and his bone terminology especially unfortunate.

A. S. ROMER

Structural Geology, with Special Reference to Economic Deposits. By BOHUSLAV STOČES and CHARLES HENRY WHITE. New York: D. Van Nostrand Co., 1935. Pp. xv+460; figs. 663. $8.00.

The translation and re-writing by Charles Henry White of Professor Stočes' *Tektonische Geologie für Montanisten*, previously published both in Czech and German, makes available in English a work that has long been recognized for the number and excellence of its illustrations and line diagrams. In the present edition, not only has the text been rearranged and expanded, but the subjects and illustrations have been increased nearly twofold.

As indicated in the subtitle, special emphasis is placed on the relation of structures to economic deposits. One-third of the text is devoted to primary structures due to (1) sedimentation, as in coal, limestone, sandstone,

clay, and gold placers; and (2) igneous action, such as in granite, basalt, and magmatic segregation of ores. The remaining two-thirds treats of secondary structures due to (1) heat, pressure, and chemical action, such as in roofing slate, anthracite, and contact metamorphic deposits; and (2) deformation of the earth's crust in producing fractures for the localization of deposits, and deformation of the foregoing structures. At the end there are chapters on surveying and mapping geologic structures, geophysical methods, and the influence of structure on mining practice.

Since the text is in reality a re-writing and not simply a translation, it has none of the awkwardness that sometimes attends the latter. Definitions of processes and their resulting structures are stated clearly and concisely; and these are illustrated with numerous photographs depicting actual structures and are accompanied by many explanatory line drawings. Of the 433 pages of text, less than twenty-five are without a photograph, structure section, or line diagram. The pictures are well reproduced on a heavy stock and only rarely do they fail to show clearly the type of structure represented. By far the greater number of illustrations and the type areas described are taken from European and British localities, and this wealth of pictorial examples from foreign areas makes the text a valuable addition to the study of structural geology in this country.

The authors have been avowedly descriptive rather than analytical, and in this sense the text may be considered an excellent primer of structural geology. Much of the material is presented in outline or tabular form. Such a purely descriptive treatment has resulted in inadequate discussions of many phases of the subject. For instance, the chapter on joints consists of only nine pages. Less than three pages are devoted to the nature of joints and their origin, ending with the statement that "the study of joints is important as they indicate direction of orogenic pressure"; but there is no discussion of how they do this, or of the various theories of pressure directions from joint analysis. The subject of drag folds and the relation of the axial planes to differential movement is disposed of in a few lines, concluding with "in the absence of other criteria the close study of drag-folds may help in recognizing whether beds are overturned or not," with no further information. No attempt is made to discuss flow cleavage or fracture cleavage as an aid in interpreting local and regional structures. In each case, however, there are numerous photographs of actual structures which illustrate excellently many points not discussed in the text. There is no mention of the work in petrotectonics of Cloos and Balk or of Sander and Schmidt.

These omissions are no doubt intentional, since in a Foreword the au-

thors limit the subject to the practical aspects and address themselves directly to mining geologists and mining engineers "with only so much of the theory of tectonics and of larger features of the structure of the Earth's crust . . . . as are essential to a knowledge of structures related to economic deposits." Because of such omissions and the absence of theoretical analysis, the text will not take the place of standard texts on structural geology; but as a supplement and reference work it should prove most valuable, and few teachers of either structural or economic geology will wish to be without it.

J. T. STARK

Journal of the Society of Petroleum Geophysics. Vol. VI, No. 1 (July, 1935).

This *Journal* is to be published semiannually by the Society of Petroleum Geophysics, a division of the American Association of Petroleum Geologists. Although styled "Volume VI," the issue of July, 1935, is the first to appear as a separate publication; the transactions of the society (1930–34) have previously appeared in the *Bulletin of the American Association of Petroleum Geologists*, or in *Physics*.

The *Journal* is especially important as an expression of the high degree of specialization in the earth sciences, and as a recognition of the need of an exclusively geophysical publication. Recognition has been accorded to geophysics by the National Research Council through the series of bulletins entitled "Physics of the Earth," but most universities give little space in their curricula to either pure or applied geophysics

The reviewer hopes that contributions will not be limited to petroleum exploration. The policy of the parent organization leads one to expect a rather generous allowance of space to articles of purely scientific interest. The inclusion of an abstract at the head of each paper would be a convenience to the reader.

H. W. STRALEY, III

"The Eastern Lupa Goldfield," by E. O. TEALE, in *Tanganyika Territory Geological Survey Department Bulletin 8*. Dar Es Salaam: Government Printer, 1935. Pp. 61; maps 3. 5*s*.

The area described in this report has produced, from the time of the first gold discovery there in 1922 to the present time, in the neighborhood of half a million pounds worth of gold from alluvial deposits. Lode deposits have not yet been worked to any important extent, but in the course of this survey about 250 quartz veins or "reefs" were located and

about ninety of them proved to be auriferous, with assays varying from a trace to over an ounce per ton. The dominant sulphide in the veins is pyrite, but some galena and chalcopyrite are present. Development work will be necessary to determine the commercial possibilities of these reefs.

The area is mainly one of gneissic granite with limited relics of the rocks into which the granite was intruded. Dike rocks of basic, intermediate, and acid composition are common and the youngest rocks of the region are erosion remnants of Tertiary lavas.

E. S. B.

"Map of the Coalfields of England and Wales." "Map of the Iron Ores of England and Wales." Issued by the Geological Survey of Great Britain. Scale, 1:1,000,000. Southampton: Ordnance Survey Office, 1935.

On the coalfield map the following units are represented by separate colors: (1) barren rocks older than Coal Measures, and Culm Measures of Devonshire; (2) Lower Carboniferous containing workable coal; (3) concealed coalfields—partly proved or probably present; (4) concealed coalfields—proved (under rocks newer than Coal Measures); (5) exposed coalfields; (6) barren Coal Measures overlying productive Coal Measures; and (7) rocks newer than Coal Measures.

The iron ores are grouped as follows: (1) pre-Carboniferous; (2) Carboniferous; (3) Lower and Middle Lias; (4) Oölites; (5) Cretaceous and Tertiary; and (6) hematite masses and veins, some magnetic and spathic ores.

R. T. C.

A Study of the Ozarkian Faunas of Southeastern Minnesota. By Louis H. Powell. Science Bulletin 1. St. Paul: Science Museum of the St. Paul Institute, 1935. Pp. 80; figs. 3; pls. 17.

In this new bulletin, Dr. Powell has described the results of intensive collection and study of the faunas of the Oneota dolomite of southeastern Minnesota, the associated Kasota sandstone, and the intermediate Blue Earth siltstone. The history and lithology of the formations are given, and the author's correlation of the stratigraphic relationships is compared with previous correlations in tabular form. The fauna of the Kasota sandstone (Ozarkian), lying between the Oneota dolomite and the underlying Jordan sandstone, is unique, and, with the exception of one species, is first described in this paper. This contribution will be helpful in the identification and correlation of Ozarkian formations.

Dan J. Jones

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